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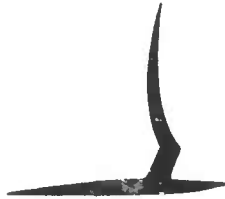
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FINAL REPORT OF THE INVESTIGATION
OF A RESONANT WAVE ENGINE

AUGUST 1956

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ABSTRACT

This report summarizes theoretical and experimental investigations of a new form of intermittent heat engine employing pressure waves for compression prior to heat addition, which were carried out at Cornell Aeronautical Laboratory between November 1951 and November 1955.

This engine consists of a number of individual parallel tubes cylindrically arranged which are opened and closed periodically by two controlled rotating valves, at the inlet and exit of the tubes. Initial studies of the basic operating principles were carried out in 1951 with a single tube model with an enlarged combustion chamber. Based upon these early studies, a multitube engine model 20 inches in diameter was constructed and tested. This multitube unit consisted of 24 individual wave tubes and was constructed primarily to investigate the effect of tube interactions upon individual tube performance and to determine the extent of the mechanical problems involved in full-scale engine operation.

The theoretical subsonic performance was investigated using the technique of the method of characteristics. The supersonic capabilities of the wavejet were also investigated and it was found that the supersonic capabilities could be determined by extrapolation of the subsonic performance data by means of similarity considerations.

In order to improve the performance of the single tube engine, tests were conducted with a constant area tube. In these tests, it was found that reignition could be achieved by use of a hot wall combustion chamber. Although an increase in specific thrust was obtained over that of the enlarged combustion chamber model the maximum experimental values were

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appreciably less than those predicted by the theoretical investigations. For example, at a Mach number 0.65 maximum available specific thrust values between 0.5 and 2.5 lbs. per square inch were obtained, whereas theoretical calculations indicated approximately 13 lbs. per square inch should be achieved. The minimum experimental specific fuel consumption values achieved were approximately 4.3 lbs. fuel per hour per lb. thrust, as contrasted with theoretically predicted values of 1.8 lbs. fuel per hour per lb. thrust.

Estimates of the supersonic performance of a shrouded wavejet, based upon the experimental subsonic performance, indicated that the specific thrust would be much less than the theoretical specific thrust of a ramjet. However, if the theoretical performance of the wavejet could be more closely approached, the performance of the wavejet would be substantially superior to that of the ramjet over the range of flight speeds investigated. It is believed that the low thrust values obtained were due, in part, to low combustion efficiency and that future emphasis should be placed upon improving the fuel injection system and fuel mixing prior to combustion.

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INTRODUCTION

The history of the application of non-steady flow phenomena to heat machines dates back to the turn of the century. The original applications were aimed at using part of the combustion energy for scavenging and for precompression by direct energy exchange between gases. When this energy transfer takes place rapidly, it can best be described as a wave process.

To the early investigators, the use of wave processes seemed very attractive, although the basic mathematical tools necessary for investigating these processes were not developed and the necessary equipment for experimental investigation of these transient phenomena was not available.

The first successful heat machine which used waves for precompression was the gas turbine of Hans Holzwarth¹. This machine consisted essentially of a constant-volume explosion chamber which supplied hot high-energy gases to a turbine through a system of valves. The scavenging and precompression were accomplished by waves created during sudden overexpansion of the exhaust gases. This overexpansion caused a high velocity inflow of cold gas, producing some precompression by hammer waves when the exhaust valve was suddenly closed. In his early machines, Holzwarth attained over-all thermal efficiencies as high as 13 per cent. Before his machine could be perfected, rapid advances in the development of the more efficient Diesel and Otto engines forced the virtual abandonment of the Holzwarth gas turbine.

Shortly after Holzwarth's disclosure, other investigators became interested in the application of nonsteady flow phenomena to aircraft jet propulsion engines². Early attempts along this line were directed toward using the Holzwarth combustion chamber which used wave precompression to

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eliminate the piston compressor of the Lorin jet-propulsion scheme.

About this time, it was also suggested that natural resonance be used to eliminate the valves of the Holzwarth combustor.

Further development of nonsteady flow engines after these early resonator-combustion types was dormant until 1930, when P. Schmidt initiated his work in propulsion. Schmidt, combining natural resonance with pressure-operated valves, developed the first successful pulsejet and won the support of the German government in 1938. With this support, the development of the pulsejet progressed rapidly, particularly at the Argus firm under Diedrich², and by 1941 the pulsejet had become the power plant for the well-known V-1 missile.

While the Germans were busy applying nonsteady flow phenomena to a missile power plant, C. Seippel, of the Brown Boveri Company of Switzerland, returned to the application of nonsteady flow to gas turbines in order to extend the operating range to higher temperatures and thereby improved efficiency. Seippel's device, called the Comprex, was perhaps the first machine utilizing pressure waves for compression which attained a competitive efficiency. Essentially, the comprex consists of a rotating cylinder with axial passages called wave guides arranged along the circumference. A system of stationary nozzles and pickups supply and draw off the gases from points along the circumference as dictated by the wave phenomena. The position of these nozzles and pickups depends on the proposed application of the unit³. By virtue of its compactness, the comprex, with little weight and space addition, was expected to appreciably increase the efficiency of a turbine power plant.

The German development of the pulsejet engine initiated interest in the fundamental nature of nonsteady flow in this country, and in 1947 a

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program was initiated for the investigation of intermittent engines under Project SQUID (Contract N6-or1-105).. The investigations under this program led to the discovery of an intermittent engine cycle which promised relatively high efficiency while retaining the simplicity of the pulsejet-type engine⁴.

In this engine, (Figure 1), a number of individual parallel tubes were opened and closed periodically by means of two controlled rotating valves located at the inlet and exhaust. Fuel which was injected in the vicinity of the exhaust valve to form a combustible mixture was then allowed to burn and be discharged. Prior to the next cycle, it was proposed that a high precompression was to be achieved by means of properly controlled pressure waves. This engine, employing wave phenomena to obtain propulsive thrust and precompression, was referred to as a wavejet engine. An experimental engine was constructed using a single tube model and it was observed that stable static operation could be sustained over a wide range of operating parameters. These experiments were described in Project SQUID Technical Memo No. CAL-35⁴.

At the conclusion of this phase, the program was transferred from Project SQUID to the Office of Naval Research (Contract No. Nonr 665-(00)). Under this program theoretical and experimental studies were carried out to determine the performance of this type of wavejet engine. The theoretical investigations of the subsonic and supersonic capabilities of this cycle^{5,6} indicated that subsonic performance would be inferior to that of the turbojet, while supersonic performance would exceed ramjet performance above the operating limits of present-day turbojet engines.

In order to investigate the performance capabilities in more detail, it was necessary to carry out a large number of cycle studies using the

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technique of the method of characteristics⁷. If the proper combustion picture and boundary conditions are employed, and if heat conduction and viscosity effects are neglected, the method of characteristics is exact. The characteristic studies were used to determine the subsonic capabilities of the wavejet engine, and from these studies it was concluded that the best specific fuel consumption values in the subsonic range were approximately twice as large as the values for the J57 turbojet engine.

Such calculations were extremely tedious, however, and in order to explore more fully the supersonic capabilities of this engine a rapid method of calculation was developed, based on similarity considerations⁶. It was found that all operating characteristics of the engine could be specified if the pressure ratio across the engine and the temperature ratio across the engine were fixed. Use of these similarity parameters made it possible to determine the supersonic performance from the subsonic performance determined from characteristic cycle studies.

In the course of these theoretical studies it was concluded that a basic improvement in the design of the wavejet could be made by properly shrouding the engine exit. Although calculations indicated that shrouding would reduce the subsonic performance by a small factor, the performance at supersonic speeds would be improved by a large factor over the non-shrouded engine performance. The performance characteristics of the shrouded wavejet were estimated over a large range of Mach numbers and air-fuel ratios, using the similarity considerations.

The results of these theoretical investigations are described in Part I of this report. Detailed discussions may be found in Ref. 5 and 6.

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In the early experimental program, tests were carried out with single tube engines with enlarged combustion chambers⁸. A full-scale multitube engine based on the best single tube configuration was constructed primarily to investigate the mechanical problems arising in such a design, and to determine the influence of adjacent tubes upon the individual tube performance.

It was observed experimentally that the multitube wavejet performance could be inferred from the performance of the individual wave tube. Consequently, further tests were carried out with single tube engines to determine the tube configuration for maximum performance.

Part II of this report summarizes the tests of single and multitube wavejet models.

PART I - THEORETICAL INVESTIGATIONS OF THE WAVEJET CYCLE

A. Single Tube Wavejet Investigations⁵

The application of the method of characteristics to the study of intermittent engines permits far more accurate estimates of periodic engine performance parameters such as thrust per unit area, specific fuel consumption, compression efficiency, and cycle time than those obtained by use of quasi-steady methods⁹.

The chief obstacles to accurate performance estimates of periodic engines are:

- (1) Lack of information concerning the combustion mode. Two idealized combustion modes were assumed for purposes of calculation. These modes were constant volume combustion and gradual heat addition.

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With one exception, all the studies were made for straight-tube configurations operating with instantaneous valve opening and closing times. Consequently, the results obtained did not apply directly to the first experimental engines, which required an enlarged combustion chamber for resonant operation, i.e., a combustion chamber area greater than the wave tube area.

(2) Difficulty in representing the correct boundary conditions during outflow and inflow. Although the assumption of instantaneously operating valves simplified the calculations, it is believed the shock losses were over-emphasized since, with finite valve opening time, shocks would form gradually and the entropy losses would consequently not be as great. On the other hand, this assumption tends to eliminate the actual losses resulting from leakage due to the finite valve closing time.

Figure 1 is a schematic diagram of a proposed propulsion unit based on a wavejet cycle. As can be seen from Figure 1, the wavejet consists of a number of parallel tubes which are alternately opened and closed at either end by two rotating valves. Fuel is injected in each tube in the region adjacent to the exhaust valve to form a combustible mixture.

Figure 2 is a typical wave diagram for this cycle constructed by the method of characteristics. At the beginning of the cycle, air is flowing through the engine and fuel is added to form a combustible mixture. The exhaust valve is closed (1) stopping the flow and causing a hammer shock (2) to move upstream. This hammer shock compresses the combustible mixture as it propagates upstream. When all of the combustible charge is compressed, the mixture is ignited and burning occurs at a constant

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rate. After undergoing complete combustion, the exhaust valve is opened, allowing the hot gases to expand in a propulsive jet (3). The arrows indicate the relative magnitude of the exhaust velocities in time.

Meanwhile the hammer shock, strengthened by combustion, continues to propagate upstream. It is followed by the interface (4), the region separating the hot and cold gases. When the shock reaches the engine inlet (5), the inlet valve is closed causing the shock to be fully reflected into the duct (6). This reflected wave aids in scavenging the engine, as evidenced by the sudden increase in exhaust velocity (7). The upstream propagating expansion wave (8) resulting from the discharge of hot gases drops the engine pressure sufficiently to induce a fresh charge upon opening of the inlet valve (9). The cycle is then repeated.

An individual air particle may be traced through the engine by following the dotted lines. With this configuration it is seen that the particle travels back and forth in the duct three cycles before reaching the combustion chamber. Each interaction of this particle with the shock introduces an energy loss through the entropy increase associated with the shock wave and results in a loss in compression efficiency.

Some of the results of these theoretical investigations are presented in Table 1 to illustrate the effect of assumed combustion mode, the ratio of the combustion chamber length to the over-all tube length and Mach number upon engine performance. It will be noted that changes in the combustion chamber length ratio, as well as diameter ratio, have a significant effect upon engine performance. By increasing the relative combustion chamber length, other parameters remaining constant, the thrust per unit area

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increases considerably with a corresponding decrease in specific fuel consumption. This effect is due to a reduction in the number of shock passages which the air undergoes prior to combustion. In Ref. 5 detailed calculations are presented for a large number of engine configurations in the subsonic range.

As can be observed from Table 1 and Figure 3, even under optimum conditions the specific fuel consumption values in the subsonic speed range were considerably larger than corresponding values for the J57 turbojet engine, although the thrust per unit area exceeds the corresponding values for this turbojet engine.

The characteristics analyses were carried out for constant area wavejets, although it was found necessary in the early experiments to use enlarged combustion chambers in order to sustain resonant operation. The experimental program was conducted at ram pressures equivalent to $M=0.35$. The theoretical studies were conducted at flight Mach numbers of $M=0$, 0.65 , and 0.95 . A considerable discrepancy was observed between the initial experimental results and the theoretical studies and it was not possible to explain the large performance discrepancies solely by Mach number effect. Consequently a wave diagram was constructed using an enlarged combustion chamber wavejet configuration with a flight speed of $M = 0.35$. This diagram showed that the increase in combustion chamber area together with the relatively small effect of lower flight speed caused an appreciable decrease in the thrust per unit area and an increase in specific fuel consumption, as indicated in Table 1. These values showed general agreement with the experimental values, and an experimental program was undertaken to develop the constant area wavejet configuration to improve the specific thrust.

B. Shrouded Wavejet Investigations⁶

The major portion of the characteristic investigations were carried out for the subsonic regime. These calculations proved to be extremely tedious. For example, the computation of the performance at one Mach number and air fuel ratio required approximately two weeks. It would

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have required a major increase in effort to obtain satisfactory estimates of the supersonic capabilities of the wavejet by the characteristic procedures. The primary problem in extending the performance capabilities was one of developing a rapid method of calculation which would give information as complete as that obtained using the non-steady flow techniques.

Application of similarity considerations to the calculation of the engine performance (See Appendix 1) shows that for an engine of given geometry all operating characteristics of the engine are specified when the pressure ratio across the engine and the temperature ratio across the engine are fixed. The temperature ratio across the engine can be varied at will by changing the air-fuel ratio. Thus, if there were a method of maintaining a constant pressure ratio across the engine as the Mach number is varied, the performance of the wavejet could be determined over the range of Mach numbers from a single characteristic diagram. It was concluded, that by employing the correct convergent-divergent nozzle, or shroud, at the wavejet exit (Figure 4), the pressure ratio across a multitube engine could be controlled. If the shroud did not adversely effect engine performance, the suggested procedure for stretching the region of applicability of a wave diagram would be successful. Upon investigation it was found that, although shrouding reduced subsonic performance by a small factor, the performance at supersonic speeds was improved significantly.

By making use of the foregoing similarity considerations, the performance characteristics of the wavejet have been estimated over a wide range of Mach numbers and air-fuel ratios. The results of these studies are as accurate as those obtained by the method of characteristics.

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The variation of sea level thrust per unit area with specific fuel consumption and Mach number is shown in Figure 3 for the shrouded wavejet and compared with the ramjet and the J57 turbojet. These calculations were carried out assuming constant area mixing, with expansion of the fully mixed exhaust to the maximum duct diameter. Preliminary analyses indicated that use of the constant area mixing chamber would not significantly increase the over-all length of the engine.

It can be seen from Figure 3 that the theoretical performance of the shrouded wavejet is superior to the ramjet. At a Mach number of 2 the wavejet has a 30 per cent lower specific fuel consumption than the ramjet.

PART II - EXPERIMENTAL WAVEJET PROGRAM

A. Single Tube Enlarged Combustion Chamber Wavejet

To test the validity of the preliminary theoretical calculations which indicated that the cycle would be stable* and that the engine would operate statically (i.e., without ram air), an exploratory model was built and first tested on December 29, 1949⁴. Since each tube of the engine could be considered to operate independently, it was possible to restrict this preliminary investigation to a single-wave tube. The preliminary experiments disclosed that a combustion chamber larger than the wave tube area was necessary to sustain periodic combustion and stable static operation.

*Stability of operation is defined for the purposes of this report as the ability of a configuration to tolerate small deviations from optimum rpm and phase position as well as the ability to operate over a wide range of fuel flows.

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Under the ONR program a test bed was designed to insure flexibility with respect to configuration changes, (Figure 5). The combustion chamber and wave tubes were of circular cross section and could easily be removed from the test-bed frame for modification. A set of valve plates covering the feasible range of open-to-closed area ratio was fabricated. Valve clearances were adjustable from scrape contact to $1/4"$ clearance. The phase relation between the inlet and exhaust valve could be controlled during a run through the use of a differential-type gear train. Valve frequency was controllable over a range of 0 to 130 cps by means of an independent electric drive.

The initial performance measured on this test bed was poor, and the static specific fuel consumption was about 12 lb. fuel per hr. per lb. thrust. However, the engine demonstrated remarkable stability, and it was possible to start the engine statically (without ram air) when the correct valve frequency and phase angle were selected before a run. The high specific fuel consumption values were not unexpected, since the initial configuration was chosen from the limited information available from the first few wave diagrams. While additional information might have been obtained from further wave diagrams, many assumptions were necessary about which there was little experimental verification. In particular, there were many possible combustion models, and when design calculations were carried out by the method of characteristics, conflicting information was obtained about valve size and phase relations. Therefore, the initial configuration was arbitrary and only served as the starting point of this program. The data obtained from this program was then used to narrow the range of configurations studied and to provide a better understanding of

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the necessary assumptions involved. A more detailed account of these experiments may be found in Project SQUID Technical Memorandum No. CAL-35, August 1951.

Since the combustion process was not accurately represented in the characteristics diagrams, the ratio of open-to-closed time could not be accurately determined. It was therefore necessary to study the effect of changes in the valve lobe angle, Figure 5. Although the actual thrust values were not always measured during a run, the mean pressure in the wave tube served as an index of performance. Previous experiments had shown that the output of a given tube geometry was always proportional to the mean pressure in the tube. The valve plates tested were of the double lobe type, with a complete wave cycle, therefore, covering 180° . Initially, the lobe angle was 90° for both the inlet and exhaust valve. After a prolonged series of runs, in which many valve plates were tested and discarded, the optimum lobe angle was found to be near 85° . A difference in lobe angle of as little as 2° was detectable in the performance. Later, these same valve plates were tested on a different wave tube geometry and the optimum lobe angle was found to be 83° for the inlet and 86° for the exhaust.

During these valve plate tests, certain anomalies were noted. A configuration which was capable of stable static operation would suddenly fail to operate statically, and even under ram conditions, the mean pressures and gross thrust values were low. A careful inspection of the wave tube and combustion chamber of these configurations revealed that failure to operate statically occurred when the exhaust port buckled slightly and increased the exhaust area. These failures were unexpected,

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since no specific investigation of such effects were conducted using the method of characteristics. It has always been assumed in these calculations that the valve plate closed instantaneously when the interface between the exhaust gas and fresh charge reached the exhaust port⁵. However, during actual wave engine operation the entire charge of hot exhaust gases may be swept out during the finite valve closing time if the exhaust port area is too large. The loss of the entire charge of hot gas appeared to suppress reignition. In order to determine the extent of this effect, a special combustion chamber was constructed with a gate valve exhaust nozzle, allowing a continuous range of exhaust areas to be tested. With this special exhaust nozzle, the allowable range of exhaust port areas was found and the optimum area determined (approximately 7/10 of the wave tube area). In view of the large effect of changes in exhaust area on the engine performance, all future configurations were optimized on the basis of this parameter. The effect was found to be most noticeable for the smaller diameter combustion chambers (below 5 inches).

The next configuration variable to be studied was the effect of valve plate clearance. Tests were made of several different configurations with the valve plate clearances varying between 1/8 inch and 1/64 inch. Unfortunately, these tests could not be conducted for clearances below 1/64 inch, as there was sufficient "wobble" in the valve plates to cause intermittent scraping, causing the required valve driving power to exceed the capacity of the drive motor. Also, the evaluation of these tests was somewhat difficult, since the test bed would warp slightly during hot operation, affecting the clearances during the run. However, it was possible, after repeated tests, to determine the range of clearances

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necessary for performance testing. All configurations tested showed marked increase in performance as the clearances were decreased to about $1/64$ inch, below this point the clearances could not be maintained. No configuration would operate statically with clearances above $3/32$ inch.

Valve plate phase relations and frequency were not investigated separately as configuration variables. Due to the ease with which these variables could be changed during each run, all data was taken at the valve phase and valve frequency of best performance. An interesting effect was noticed during these tests, which greatly aided in selecting the proper phase relation between valve plates. While the engine was being adjusted and phase angle changed, the noise level to an observer facing the inlet valve would be reduced suddenly and markedly when the proper phase was reached. This noise reduction was in agreement with the wave diagrams⁵, which indicated that for proper phasing, the combustion pressure wave should be fully reflected back into the tube. The increase in noise, caused by out-of-phase operation, was due to part of this combustion pressure wave escaping through the inlet.

The single tube test bed was modified to facilitate changes in combustion chamber geometry since theoretical studies⁵ and previous single tube tests had shown that combustion chamber modifications had the greatest effect upon the engine performance. It was also desired at this time to test the single tube engine under ram conditions. Therefore, a sealed diffuser cowl section connected to a venturi-type flowmeter (Figure 6) was mounted around the inlet valve section. The volume of the cowl section was sufficient to damp out nearly all nonsteady flow oscillations created at the engine inlet allowing steady mass flow measurement at the venturi.

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The net thrust was then computed by subtracting from the measured gross thrust the inlet momentum term¹⁰.

The first combustion chamber tested had a length ratio of 1/2.

This designation is used to describe that fraction of the total engine length which the combustion chamber occupies. This selection was influenced by the theoretical studies which indicated that increased combustion chamber length would improve the engine performance. While this engine resonated with ram air, it was not sufficiently stable for static operation or the measurement of performance. In view of the poor performance of this combustion chamber, an engine with a combustion chamber length ratio of 1/4, similar to an engine that had been previously tested on the early single tube test bed, was mounted to determine whether the test bed modifications had adversely affected the engine operation. This configuration was stable and operated statically over a wide range of air-fuel ratios.

With this configuration, gross thrust values of up to 2 psi (based on the diameter of the wave tube) were obtained with a specific fuel consumption of approximately 3 lb./hr./lb. While there was considerable scatter from run to run, it was apparent that there was a sharp increase in specific fuel consumption at lower air-fuel ratios. With this configuration, as well as with subsequent configurations, the engine was found to be extremely sensitive to changes in valve clearances and exhaust port area. Although these changes in configuration were small and difficult to eliminate, their effect upon engine performance was evidenced by the scatter of the test results. The valve clearances and exhaust port areas would vary during hot operation and from one test run to another as a result of the accumulation of permanent damage arising from thermal stresses.

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After completion of the static tests, the cowling was installed and the engine was tested to the limit of blower supply air ($M = 0.40$). The measured thrust per unit area did not differ appreciably from the values obtained in the static tests, indicating no marked ram effects at these low Mach numbers. Visual inspection of the exhaust at maximum fuel flow led us to suspect that considerable burning was taking place outside the tube. Consequently, Orsat equipment was installed in an effort to determine the combustion efficiency by the analysis of the exhaust gases. After a series of tests, the Orsat-measured air-fuel ratios were found to differ from the air-fuel ratio as determined by measured mass flow. It was suspected that this discrepancy was due to the nonsteady nature of the engine exhaust, and after a series of tests with various sampling pipes it was concluded that this method of analysis could not be used in its present form. Its use was therefore discontinued.

Recalling that the $1/4$ combustion chamber length ratio exhibited far more stability than the $1/2$ combustion chamber length ratio engine, it was decided to shorten the combustion chamber length ratio to $1/5$, in order to determine whether the optimum combustion chamber length had been reached. With a ratio of $1/5$, the engine performance was superior with respect to stability, although the maximum thrust per unit area was decreased. However, at high fuel flows, the increase in specific fuel consumption was even more marked than when the combustion chamber length ratio was $1/4$. Since the fuel injectors were closer to the exhaust port, it was suspected that this engine discharged more unburned fuel. In an attempt to alleviate this situation, the fuel injectors were modified so as to inject directly upstream, but no apparent improvement was observed.

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Next the injection system was replaced with small capacity fuel nozzles mounted on the forward reducing section of the combustion chamber, and operated at increased fuel injection pressure. A specific fuel consumption of $2.3 \frac{\text{LB}}{\text{HR}}$ was obtained with this engine with the latter method of fuel injection.

In order to complete the study of the effect of combustion chamber length upon engine performance the combustion chamber of length ratio 1/5 was replaced with a combustion chamber of length ratio 3/10. While this configuration yielded approximately the same maximum thrust per unit area, the specific fuel consumption was somewhat higher and the engine operation less stable.

The performance of these engine configurations is summarized in Table 2. The data indicated that the shortest combustion chamber tested had the lowest specific fuel consumption and exhibited the greatest stability. However, the thrust per unit area of the longer combustion chamber length ratios was somewhat higher. It should be pointed out here that none of the configurations tested have demonstrated the high thrust per unit area predicted by the method of characteristics, Table 1. In view of this poor correlation with theory, a more detailed study of the engine cycle was carried out. This theoretical study involved the same assumptions and procedures used in the previous theoretical engine studies, with the exception that an enlarged combustion chamber was assumed, having a combustion chamber to wave tube area ratio of 2. The study indicated a marked decrease in the theoretical performance with increased combustion chamber area, Table 1, and thrust per unit area values more in agreement with experiment results, Table 2.

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B. Multitube Wavejet Engine

In order to study the relationship between the multitube and single tube performance and investigate the mechanical problems peculiar to the multitube engine, a 24-tube unit was designed and constructed. The individual wave tube design was based upon the geometry employed in the single tube configuration yielding the best performance. However, the cross-sectional area of each tube was sector-shaped rather than circular. The single tube cross-sectional areas and area ratios were maintained and the included angle of each tube was selected to be 15° , so as to form a completely symmetrical engine with 24 individual tubes, Figs.7, 8, and 9.

The exhaust valve was designed as a centrifugal pump which would induce air through the engine core and expell it through the valve periphery to aid in valve cooling. The combustion chambers received fuel from a common manifold. Four equally spaced wave tubes were ignited by an external spark ignition system, while the remaining tubes were ignited by controlled hot gas leakage through combustion chamber ports. In addition, the engine was equipped with a differential-type phase changer to regulate the phase difference between the inlet and exhaust valve during operation. For measurement of thrust, the multitube wave engine was mounted on a null-type indicating thrust stand. The inlet momentum was determined by measurements of the mass flow in the intake diffuser which was attached to the engine inlet and connected to the high pressure air supply system, Figs.8 and 9.

During tests with this engine, although stable multitube operation could be obtained, thermal stresses resulted in the warpage of the valve plate and distortion of the engine supports, which resulted in valve binding.

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Although the effect of the thermal stresses on the exhaust valve was reduced by water cooling, the combustion chambers became so badly warped that testing of all 24 units could not be carried out without considerable engine repair. The severe warpage of the combustion chamber prevented operation of a number of the wave tubes, resulting in a low average combustion chamber pressure (Table 2). In addition, the tubes which were in operation exhibited widely differing mean engine pressures in contrast to the evenly balanced pressures observed in preliminary tests.

Before tests with the multitube unit engine were discontinued, a number of tests were carried out with the individual tubes which showed the greatest distortion. Resonant operation could be sustained in these units using ram air, although the measured performance was much lower than that previously obtained with single tube units of circular cross section.

During the valve development program, tests were also carried out to determine the effects of tube interactions upon single engine performance. In order to observe these tube interactions, the individual tubes of the multitube engine were operated singly and in groups. From these experiments, it was concluded that the tube interactions did not adversely affect the performance, inasmuch as multitube operation resulted in small favorable increases in mean engine pressures. However, the observed specific values of the individual tubes and the multitube units were low compared with the improved single tube data which was then becoming available. Since it appeared that the performance of the multitube engine could be determined from studies of the single tube unit, further tests were restricted to investigations with single tube units.

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C. Constant Area Wavejet Engine

The theoretical results summarized in Table 1 indicated that a major improvement in engine performance could be achieved by employing a combustion chamber diameter equal to that of the wave tube, as illustrated in Figure 2. In particular, the calculations indicated that the straight-tube engine would possess a much higher thrust per unit area than the enlarged combustion chamber configuration.

Early attempts to maintain burning in a straight-tube were not successful. Experiments at the Aerophysics Development Corp.¹¹ indicated that combustion could be sustained in a straight-tube by heating the combustion chamber walls to temperatures sufficient to support ignition. The hot wall combustor technique was immediately considered as a method of reducing the combustion chamber diameter of the C.A.L. wavejet while sustaining combustion.

In order to obtain some degree of wall temperature control, various thicknesses of asbestos tape were wrapped around the combustion chamber. The preliminary tests with this configuration were conducted to determine the amount of insulation necessary for high wall temperatures and reasonably long chamber life. The combustion chamber temperatures were recorded during these tests with an optical pyrometer and the necessary wall temperature was found to be approximately 1600°F. These tests also indicated that the engine could be made to resonate and to yield gross specific thrusts of 3 psi at moderate fuel consumptions. In addition, it was noted that the increased mean engine pressure exceeded the fuel injection pressures available and reduced the fuel flow in the engine. To counteract the effect of the higher mean engine pressures and to improve fuel

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atomization, a high pressure fuel supply and metering system was installed. This system incorporated a Potter turbine type electronic flow indicator with a pressure range of 0-1000 psi and fuel flow range of 0.07 to 7.0 gpm.

To evaluate the effects of the important engine variables such as fuel injection system, valve angle, and valve speed upon the engine performance of the constant area wavejet engine, tests were conducted in a low pressure free air blast of 0-250 mph. The fuel injection system was studied first to determine the optimum location, size and number of fuel injectors and fuel injection pressure. Fuel injectors were installed individually and in combination at various locations along the axis of the engine directed both upstream and downstream, as well as radially. The results of these tests indicated that the best fuel system evaluated consisted of two low capacity fuel injectors (7.5 gph), diametrically opposed at a point midway along the axis of the wavejet (upstream of the combustion chamber), operating near the maximum fuel injection pressure.

During the second phase, tests were carried out to determine the effect of changes in valve plate configuration upon engine performance. The results of this program were inconclusive, since the effect of valve clearances far outweighed the effect of changes in valve lobe angle. However, the most stable valve configuration utilized an inlet valve with a lobe angle of 83° and an exhaust valve with a lobe angle of 86° .

In view of the dominating influence of the valve leakage upon engine performance, a program was undertaken to reduce the valve clearance. New valve plates were installed and the cold clearances adjusted to about 0.020 in. Initial tests with this engine yielded mean engine pressures of 12 psi gage (approximately twice previously attained maximum mean engine

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pressures) with about 18 lbs. gross thrust. Further refinements made it possible to adjust the exhaust valve cold clearances to values as low as 0.0015 in. However, during resonant operation with these clearances it was observed by sighting across the engine exhaust ports, that the valve clearances increased considerably. It was possible that this effect resulted from some type of valve distortion or deflection during resonant operation. This possibility was investigated by using thicker valve plates. A noticeable improvement in performance was achieved with these valves.

The results of these low Mach number tests are summarized in Fig. 10 and 11. Due to the sensitivity of the experimental engine to valve phasing, valve speed, valve clearances and the physical condition of the engine, there was a considerable scatter in the test data. In order to simplify the qualitative interpretation of the test data, only the upper and lower limits have been plotted.

Since improved specific thrusts were obtained with the hot wall combustion chamber wavejet at low subsonic Mach numbers, tests were extended to the higher subsonic range, in order to evaluate the effect of Mach number upon engine performance. The air supply used for these tests consisted of a V-1710 Allison aircraft engine driving an Allison V-3420 double-stage supercharger. The initial wavejet engine configuration tested was based upon the previous low speed tests. These tests were conducted at ram air total pressures of up to 11 psig. From these tests it was evident, Fig. 12, that the engine operated at choked exhaust conditions with ram total pressures of 6 psig and above. This engine exhibited gross specific thrusts of 3 to 3-1/2 lbs. per sq. inch with

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specific fuel consumption based on a gross thrust of 4 lbs. of fuel per hour per lb. thrust and mean engine pressures of up to 2 atmospheres gage. Improved gross specific thrusts of 4 and 4-1/2 lbs. per sq. inch at a ram total pressure of 10 psi were obtained during additional tests.

In order to determine the extent of inlet momentum losses for thrust corrections, a 4" x 2" venturimeter was connected directly to the high speed air supply and to a sealed diffuser around the engine inlet. The latter connection consisted of a fixed bellows to allow for thrust measurement. The results of tests under these conditions indicated considerably lower values of gross specific thrust (1-1/2 to 2 psi) than were previously obtained. In view of the apparent adverse affects of the venturimeter upon the wavejet engine performance, the venturimeter was removed to verify the earlier performance data. The gross specific thrust was again observed to be about 4 psi.

An alternate method of determining the inlet momentum losses employed a disconnected air supply with pressure survey rakes located in the constant area section of the sealed diffuser. These tests indicated no adverse effects upon the engine performance but rather, with improved exhaust valve clearances, higher gross specific thrust of over 6 psi were observed, and, in addition, yielded necessary information for the calculation of the inlet losses, Fig. 13. Fig. 14 to 17 summarize the performance of the single tube constant area wavejet, corrected for inlet momentum losses.

The high pressure tests indicated that a choked-exit condition was obtained. Since at the choked-exit condition the engine performance would not be sensitive to ambient pressure conditions at the exit, it became possible to extrapolate the subsonic performance of this engine to determine

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the supersonic capabilities in the same manner in which the theoretical calculations of the subsonic performance were extrapolated to determine the supersonic capabilities.

The supersonic performance based on the observed pressure and temperature ratios obtained in the high pressure experimental tests was calculated, assuming that the supersonic geometry would be that of Figure 4, and that the pressure and temperature ratios across the wave tube remained constant. The results of these extrapolations are shown in Figures 18 and 19, and are compared with the performance of the J-57 turbojet and the ramjet at sea level conditions.

Figure 18 is a comparison of the available specific thrust as a function of flight Mach number for the wavejet based on the maximum observed experimental performance. The extrapolated thrust capabilities of this engine indicated very low specific thrust values when compared with the ramjet above a Mach number of 1. At a Mach number of 2 the value of specific thrust was approximately one-fourth that of the ramjet. Figure 19 indicates, however, that somewhat lower specific fuel consumption values would be obtained.

Previous extrapolations of the shrouded wavejet performance based upon the results observed at a Mach number of 0.3 indicated that the specific thrust would be approximately 30 per cent greater than that of the ramjet with a corresponding decrease in the specific fuel consumption. The experimental investigations at high subsonic Mach numbers indicated that the increase in performance expected as a result of the increase in ram pressure was not achieved. Figure 17 shows the extrapolated thrust increase as compared with that observed experimentally. This large discrepancy

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is believed to be primarily due to extremely poor combustion efficiencies at the higher ram pressures. This is further illustrated in Figure 20, where the calculated performance of the individual wave tube is compared with the best observed experimental values. The measured air-fuel ratios indicate excessively rich air-fuel mixtures. The use of the high pressure Monarch nozzle fuel injection system may have resulted in extremely poor mixing prior to combustion, as well as excessive waste of fuel, since the burning process was intermittent.

CONCLUSIONS

The results of the theoretical investigations of the wavejet engine have suggested that the wavejet shows considerable promise as a supersonic power plant. The characteristic investigations which were carried out to determine the subsonic performance have shown that relatively large values of specific thrust can be achieved in these engines, although the specific fuel consumption values are approximately twice as large as those of conventional turbojet engines. Optimum specific thrust values at a Mach number of 0.65, for example, were calculated to be approximately 12 lbs. per sq. inch, with corresponding specific fuel consumption values of 1.9 lbs. of fuel per hour per lb. thrust. These studies were made with straight-tube wavejet configurations. Studies were also carried out for wave tubes with enlarged combustion chambers and indicated that the performance would be considerably decreased with this configuration.

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In the supersonic range the performance capabilities of the multi-tube engine were determined by the application of similarity considerations which enabled the extrapolation of subsonic characteristic calculations to the supersonic regime. It was found that this procedure could be applied, provided choked exit conditions across the engine were obtained, which permitted the pressure ratios and temperature ratios across the engine to be held constant. It was found that by properly shrouding the wavejet, the pressure ratios could be controlled. Large gains in performance were predicted with proper shroud design. The results of these studies indicated that the wavejet should be superior in performance to the ramjet at supersonic speeds, and, consequently, suggested that the wavejet shows considerable promise as a supersonic power plant.

The experimental performance of the individual wave tubes has not as yet indicated values in agreement with the theoretical predictions. Tests with the early single tube units indicated extremely poor specific thrust and specific fuel consumption values which could primarily be attributed to the enlarged combustion chamber geometry employed. These tests did indicate, however, that stable static operation could be achieved over a wide range of operating parameters.

The characteristics investigations were carried out under the assumption that each tube of the engine could be considered as a separate unit. A multitube engine was constructed, based on the early wave tube design, to investigate primarily the effect of tube interactions upon individual tube performance and to determine the effect of major problems involved in the full-scale engine operation. These tests showed that the presence of adjacent tubes did not adversely affect the individual tube

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operation and, consequently, that future investigations could be restricted to single tube studies. A number of mechanical problems were observed, primarily as a result of warpage of the combustion chamber walls and valve plates due to the high temperatures, which made the maintenance of close valve clearances difficult. Although valve warpage problems were solved, the internal wall warpage problems were not eliminated in the tests.

In order to improve performance of the single tube engine, tests were conducted with constant area tubes. In these tests it was found that reignition could be achieved by use of a hot wall combustion chamber. Simulated Mach number tests with this configuration indicated that at ram pressures corresponding to high subsonic speed ranges, maximum values of available thrust were of the order of 5.5 lbs. per sq. inch with specific fuel consumption values of approximately 3.5 lbs. of fuel per hour per thrust. It was observed in these tests that choked exit conditions were obtained during the exhaust discharge.

The supersonic performance studies extrapolated from the experimental results observed at a Mach number of 0.3 indicated the possibility of a substantial gain in performance over that of the ramjet operating in a supersonic range with the same air-fuel ratios. It was found, however, that the expected increase in performance in the subsonic range based on the extrapolated performance from a Mach number of 0.3 was not achieved in the experimental program.

The extrapolated performance indicated that thrusts of approximately 9 lbs. per sq. inch should be achieved at a Mach number of 0.8, whereas, experimentally, approximately 3 lbs. per sq. inch were obtained, which increased to approximately 5.5 lbs. per sq. inch at a Mach number of 0.95.

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The supersonic performance based on the extrapolated values of highest subsonic Mach number data indicated the thrust values would be approximately $1/4$ that of the ramjet in the supersonic range, although the specific fuel consumption values would be slightly lower.

The major experimental problem that exists is the achievement of increased specific thrust values, in order to approach more closely the predicted theoretical performance. It is believed that this improvement can be attained through the use of improved fuel injection systems and fuel mixing to increase the combustion efficiency. It is concluded that the wavejet would prove to be a promising supersonic power plant if improved specific thrust values can be obtained.

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REFERENCES

1. Stodola, A. and Loewenstein, L.C., Steam and Gas Turbines, Vol. I and II, McGraw-Hill, New York and London (1927)
2. Diedrich, G., The Aeroresonator Power Plant of the V-1 Flying Bomb, translated by A. Kahane, Project SQUID Technical Memorandum No. PE-4 (30 June 1948)
3. Norman, C.A. and Zimmerman, R.H., Introduction to Gas Turbine and Jet Propulsion Design, Harper and Bros., New York (1948)
4. Hertzberg, A. and Logan, J.G., A New Form of Heat Engine Utilizing Pressure Waves, Project SQUID Technical Memorandum No. 35 (15 August 1951) (CONFIDENTIAL)
5. Logan, J.G., Theoretical Studies of the Performance of Heat Engines Using Pressure Waves, Cornell Aeronautical Laboratory Report No. DD-799-A-1 (December 1954) (CONFIDENTIAL)
6. Lawrence, H.R. and Weatherston, R.C., The Capabilities of the Shrouded Wavejet Engines, Paper delivered at Intermittent Engine Symposium, Princeton University, Princeton, New Jersey 9-10 November 1954 (CONFIDENTIAL)
7. Rudinger, G., Wave Diagrams for Nonsteady Flow in Ducts D. Van Nostrand, New York (1955)
8. Hertzberg, A. and Russo, A., Experimental Investigation of a Resonant Wave Engine, Cornell Aeronautical Laboratory Report No. DD-799-A-2 (December 1954) (CONFIDENTIAL)
9. Foa, J.V., Single Flow Jet Engines - A Generalized Treatment, J.A.R.S., p. 115 (September 1951)
10. Weatherston, R.C., Thrust and Drag, Journal of the American Rocket Society, November-December 1952
11. Holloy, W. and Bitando, D., Preliminary Progress Report on the Experimental Performance of the Multijet Engine, Paper delivered at Intermittent Engine Symposium Princeton University, New Jersey, 9-10 November 1954 (CONFIDENTIAL)

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APPENDIX I

SHROUDED WAVEJET CALCULATIONS

SYMBOLS

P_T = total pressure

p = static pressure = $\rho g R T$

t = time

t_c = cycle time for nonsteady engine

T = static temperature

θ = total temperature

A = area

g = acceleration of gravity

M = Mach No.

a = speed of sound = $(\gamma g R T)^{1/2}$

γ = $C_p / C_v = 1.4$

C_p = specific heat = 0.24 BTU/LB/°F

U = velocity

V = volume

ρ = density

η_c = combustion efficiency

Q = heating value of fuel = 19,200 BTU/LB

α_s = stoichiometric air-fuel ratio

$\tau = \frac{\eta_c Q}{C_p \theta} \frac{\phi}{\alpha_s}$

α = air-fuel ratio

α_0 = air-fuel ratio at $M = 0$ that would produce the same value of τ that α produced at another Mach No.

T = thrust

m = mass flow = $\sqrt{\frac{\gamma}{g R}} \frac{P_T A D}{\sqrt{\theta}}$

F = stream force = $P A (1 + \gamma M^2) = \sqrt{\frac{g R}{\gamma}} \frac{m \sqrt{\theta}}{N}$

C_T = coefficient of thrust = $\frac{F/A}{P_0}$

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$$C_I = \frac{3600 g}{a_o C \alpha}$$

C = SFC = specific fuel consumption (lb.fuel per hr/lb.thrust)

$$\beta_1 = \int_0^1 \frac{P_f}{P_i} (\gamma M_f^2 + 1) d\alpha$$

$$\beta_2 = \int_0^1 \frac{P_f}{P_i} \frac{a_i}{a_f} M_f d\alpha$$

$$D = M \left[1 + \frac{\gamma-1}{2} M^2 \right]^{-\frac{\gamma+1}{2(\gamma-1)}}$$

$$G = \left[1 + \gamma M^2 \right] \left[1 + \frac{\gamma-1}{2} M^2 \right]^{-\frac{\gamma}{\gamma-1}}$$

$$N = M \left[1 + \frac{\gamma-1}{2} M^2 \right]^{\frac{1}{2}} \left[1 + \gamma M^2 \right]^{-1}$$

Stations

- o Atmospheric or free flight
- 1 Stagnation conditions at end of diffuser and entrance to engine
- e Condition immediately inside wave tube exit
- 2 " " " " " " outside " " " "
- 3 Final steady state condition of mixed flow for shrouded engine
- f Shroud exit condition, for unshrouded wave engines: $P_e = P_f$

$$P_2 = P_o$$

$$V_f = V_e$$

NOTE: Mach number functions F,D,G,N are presented and tabulated in Cornell Aeronautical Laboratory Report "Mach Number Functions for Ideal Diatomic Gases" by J. V. Foa, October 1949.

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GENERAL ASSUMPTIONS

1. Ambient Static Temperature $\theta_0 = 530^{\circ}\text{R}$
2. Ambient Static Pressure $P_0 = 14.7 \text{ psi}$
3. Ratio of Specific Heats $\gamma = 1.4$
4. Specific Heat at Constant Pressure $C_p = 0.24 \text{ BTU/lb}^{\circ}\text{F}$
5. Heating Value of Fuel $Q = 19,200 \text{ BTU/lb.}$
6. Equal Static and Stagnation Conditions at the Diffuser Exit
7. Thrust per Unit Area is Based on the Maximum Engine Area

TABLES

TABLE 1 - ASSUMED DIFFUSER PRESSURE RATIO

M_0	Theoretical P_1/P_0	Assumed P_1/P_0
0.0	1.00	1.00
0.5	1.19	1.13
1.0	1.89	1.80
1.5	3.67	3.48
2.0	7.82	6.72
3.0	36.73	20.20
4.0	151.80	41.00

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The thrust is defined to include all internal and external forces acting on the propulsion device in the direction of its axis,

$$T = M_f V_f - M_0 V_0 + A_f (P_f - P_0). \quad (1)$$

Irreversible external flow contributions are not included. For nonsteady flow propulsion devices, the average thrust is given by

$$T = \frac{\int_0^{t_c} (V_f - V_0) m_f dt}{t_c} + \frac{\int_0^{t_c} (P_f - P_0) A_f dt}{t_c} \quad (2)$$

where t_c is the cycle time.

It is convenient for calculation purposes to express the performance equations in terms of pressure, speed of sound, and Mach number. In dimensionless form, the thrust Eq. (1) may be written as

$$C_T = \frac{T/A}{P_0} = \int_0^1 \frac{P_f}{P_0} (\gamma M_f^2 + 1) d\alpha - \gamma M_0 \int_0^1 \frac{P_f}{P_0} M_f \frac{a_0}{a_f} d\alpha - 1 \quad (3)$$

The air specific impulse $\frac{3600}{\alpha c}$ may also be expressed in a dimensionless form as

$$C_I = \frac{3600 g}{c \alpha a_0} = \frac{\int_0^1 \frac{P_f}{P_0} (\gamma M_f^2 + 1) d\alpha - 1}{\int_0^1 \frac{P_f}{P_0} M_f \frac{a_0}{a_f} d\alpha} \quad (4)$$

These equations may be written, more conveniently, in the form

$$C_T = \frac{P_1}{P_0} \beta_1 - M_0 \frac{P_1}{P_0} \frac{a_0}{a_1} \beta_2 - 1, \quad (5)$$

and

$$C_I = \frac{\frac{P_1}{P_0} \beta_1 - 1}{\frac{P_1 a_0}{P_0 a_1} \beta_2} - M_0 \quad (6)$$

where

$$\beta_1 = \int_0^1 \frac{P_f}{P_1} (\gamma M_f^2 + 1) d\alpha \quad (7)$$

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and

$$\beta_2 = \gamma \int_0^1 P_t/P_1 \cdot a_1/a_t \cdot M_t d\alpha \quad (8)$$

The values of β_1 and β_2 depend only upon the engine characteristics and the coefficients, and the remaining terms depend only upon the diffuser efficiency and flight Mach number.

The values of β_1 and β_2 for the different wave engine configurations were obtained from Reference 1. β_1 and β_2 are related to the thrust per unit area and specific fuel consumption from the characteristics diagrams by:

$$\beta_2 = \frac{a_1 \kappa \alpha (T/A)}{3600 P_1 g} \quad (9)$$

and

$$\beta_1 = a_0/a_1 \beta_2 (C_1 + M_0) + P_0/P_1 \quad (10)$$

The performance of any engine configuration compounded with the wave engine may be determined at any Mach number as long as the temperature rise ratio and the pressure ratio across the wave engine component corresponds to that of the particular characteristic cycle selected. Consequently, performance calculations from a single characteristics diagram can be employed to determine the performance of engine configurations over a wide range of air-fuel ratios and flight Mach numbers.

For nonsteady engines, an average exhaust temperature may be defined, as in the steady flow case, by

$$\theta_e = \theta_1 + K/\alpha \quad (11)$$

where K is a function of the heat content of the fuel, the combustion efficiency and the mode of heat addition.

For different inlet stagnation temperatures θ_0 and θ_1 , the temperature ratio θ_e/θ_1 is constant if

$$\frac{\theta_e}{\theta_1} = 1 + \frac{K}{\alpha \theta_1} = 1 + \frac{K}{\alpha_0 \theta_0} \quad (12)$$

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In order to maintain a constant temperature ratio, it is only necessary to maintain $(\alpha \theta_1)$ constant. Since $\theta_1 = \theta_0 \left[1 + \frac{\gamma-1}{2} M_0^2 \right]$ we can write

$$\alpha \theta_0 \left[1 + \frac{\gamma-1}{2} M_0^2 \right] = \alpha_0 \theta_0$$

or

$$\alpha = \frac{\alpha_0}{1 + \frac{\gamma-1}{2} M_0^2} \quad (13)$$

where α_0 is the air-fuel ratio at $M_1 = 0$ and α is the air-fuel ratio at any Mach number (M_0).

If the air-fuel ratio at ($M_0 = 0$) is 60, the change in air-fuel ratio required to maintain θ_e / θ_1 constant at any other flight Mach number, is given by

TABLE 2

M_0	α
0	60 = α_0
1	50
2	33
3	22
4	15

In the case of the shrouded wavejet engine, the assumptions are:

1. Mixing of the exhaust gases takes place in a constant area tube.
2. Wall friction forces are neglected.
3. The flow is uniform and steady at the end of mixing.

The inlet of the engine is connected to a plenum and the exit of the engine exhausts to a constant area mixing chamber. By proper design of the converging-diverging exhaust shroud it is possible to maintain a constant pressure ratio across the wave tubes at supersonic speeds.

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In order to evaluate the performance of the shrouded wave engine, it is necessary to determine the final steady flow condition of the mixed exhaust gases. The momentum relation applied between stations (e) and (3) yields

$$\int_0^{A_{total}} p_e (1 + \gamma M_e^2) dA_e = \sqrt{g R / \gamma} m_e \sqrt{\theta_e / N_3}$$

where

$$m_3 = \frac{\int_0^{t_c} m_e dt}{\int_0^{t_c} dt}$$

and t_c is the cycle time.

Substituting

$$m = \rho V A$$

$$p = \rho g V T$$

$$a = \sqrt{\gamma g R T}$$

$$t = \delta t_c$$

$$A = A_{MAX}$$

yields

$$N_e = \frac{\theta_3}{\theta_1} \frac{\int_0^1 p_e / p_1 a_1 / a_e M_e d\alpha}{\int_0^1 p_e / p_1 (1 + \gamma M_e^2) d\alpha}$$

or

$$N_3 = \frac{T}{\gamma} \sqrt{\frac{\theta_3}{\theta_1}} \frac{\beta_3^{(1/\gamma) n_c}}{\beta_1^{(1/\gamma) n_c}}$$

where

$$\frac{\theta_3}{\theta_1} = \sqrt{1 + \frac{Q n_c}{C_p \theta_1}}$$

The Mach number at the end of mixing (M_3) is determined from N_3 above. The equation of continuity yields

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$$M_3 = \gamma \int_0^1 \frac{P_e M_e}{a_e} d\alpha = \sqrt{\frac{\gamma}{gR}} \frac{P_3 D_3}{\sqrt{\theta_3}}$$

which may be combined with the equation for N_3 and $D_3 = G_3 N_3$ to yield

$$P_{T3}/P_1 = (\text{compression ratio}) = B_1/G_3$$

In order to maintain the boundary conditions at the end of the wave tube the exit of the mixing chamber is terminated by a nozzle expanded to the original diameter of the wave engine. The total pressure of the mixed flow must be sufficiently greater than the atmospheric static pressure, to which the flow is discharging, to maintain the supersonic Mach number determined by the area ratios. These conditions are satisfied for the shrouded wave engine when the exhaust is choked.

From isentropic continuity conditions,

$$D_{3\text{subsonic}} = 3/4 D_{f\text{supersonic}}$$

assuming that the core of the wave engine is 1/3 of the total wave tube area.

M_f may be determined from D_f and

$$\frac{P_{T3}}{P_1} = \frac{P_{T3}/P_1}{\left[1 + \frac{\gamma-1}{2} M_f^2\right]^{\frac{\gamma}{\gamma-1}}} = \frac{B_1/\theta_3}{\left[1 + \frac{\gamma-1}{2} M_f^2\right]^{\frac{\gamma}{\gamma-1}}}$$

$$a_1/a_f = \sqrt{\theta_1/\theta_f \left(1 + \frac{\gamma-1}{2} M_f^2\right)}$$

The values used to extrapolate the subsonic engine performance are shown in Table 3.

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Table I
THEORETICAL WAVEJET ENGINE PERFORMANCE
CONSTANT AREA WAVEJET ENGINE PERFORMANCE *

MACH NO.	COMBUSTION CHAMBER LENGTH RATIO	AIR FUEL RATIO	MODE OF HEAT ADDITION	PRESSURE AFTER HEAT ADDITION ATMOSPHERES	SPECIFIC FUEL CONSUMPTION lbs. fuel hr. lb. thrust	SPECIFIC THRUST lbs/sq.in.
0.65	0.25	33	CONSTANT VOLUME COMBUSTION	11.65	2.4	10.7*
0.65	0.25	33	GRADUAL HEAT ADDITION	4.61	3.0	6.1
0.65	0.50	33	CONSTANT VOLUME COMBUSTION	9.56	1.9	12.8
0.65	0.50	33	GRADUAL HEAT ADDITION	12.19	1.8	14.5
0.95	0.50	33	CONSTANT VOLUME COMBUSTION	11.50	2.1	15.9
0.95	0.50	33	GRADUAL HEAT ADDITION	11.41	2.0	16.0

ENLARGED COMBUSTION CHAMBER WAVEJET ENGINE PERFORMANCE $\left(\frac{\text{combustion chamber area}}{\text{wave tube area}} \right) = 2^{**}$

MACH NO.	COMBUSTION CHAMBER LENGTH RATIO	AIR FUEL RATIO	MODE OF HEAT ADDITION	PRESSURE AFTER HEAT ADDITION	SPECIFIC FUEL CONSUMPTION lbs. fuel hr. lb. thrust	SPECIFIC THRUST lbs/sq.in.
0.35	0.25	33	CONSTANT VOLUME COMBUSTION	5.85	2.8	1.7

*Summarized from CAL Rep. No. DD-799-A-1
**Summarized from CAL Rep. No. DD-799-A-2

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Table 2
SUMMARY OF EXPERIMENTAL WAVEJET ENGINE TEST RESULTS

ENLARGED COMBUSTION CHAMBER
SINGLE TUBE WAVEJET ENGINE PERFORMANCE $\left(\frac{\text{combustion chamber area}}{\text{wave tube area}} \right) = 2$

PERFORMANCE AT MAXIMUM AND MINIMUM SPECIFIC FUEL CONSUMPTION				
COMBUSTION CHAMBER LENGTH RATIO	SPECIFIC FUEL CONSUMPTION	SPECIFIC THRUST	AIR FUEL RATIO	MACH NO.
1/5	2.3	0.75	—	0
1/5	9.3	1.75	—	0
1/5	3.5	1.0	60	0.36
1/5	9.0	1.6	20	0.36
1/4	3.1	0.9	—	0
1/4	9.5	2.0	—	0
1/4	4.5	1.3	70	0.36
1/4	8.2	1.4	60	0.36
3/10	4.0	1.5	—	0
3/10	6.9	1.2	—	0
3/10	4.8	1.1	60	0.36
3/10	6.0	0.6	85	0.36

MULTITUBE WAVEJET ENGINE PERFORMANCE

MACH NO.	MEAN ENGINE PRESSURE (IN HG)	GROSS THRUST (LB.)	NET THRUST (LB.)	FUEL SPECIFIC IMPULSE (SEC.)	SPECIFIC FUEL CONSUMPTION (LB./HR.) LB.	AIR SPECIFIC IMPULSE (SEC.)	AIR FUEL RATIO
0.23	3-7	120	66.8	238	15.11	10	23.8

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Table 3
EXPERIMENTAL ENGINE

$$M_o = 0.9$$

$$\eta_c = 0.90$$

$$Q = 19200$$

$$\frac{T}{A} = 4.15$$

$$P_o = 14.7$$

$$C_p = 0.24$$

$$C = 3.9$$

$$\theta_o = 530$$

$$\gamma = 1.4$$

$$\alpha = 12.5$$

$$\beta_s = \frac{a_1 C (T/A)}{3600 P_1 g} = \frac{(1128.5)(3.9)(12.5)(4.15)}{(0.928)(3600)(24.25)(32.2)} = 0.0874$$

$$\beta_1 = \frac{a_o}{a_1} \beta_s (C_s + M_o) + P_o/P_1 \quad C_s = \frac{3600g}{C \alpha a_o} = \frac{(3600)(32.2)}{(3.9)(12.5)(1128.5)} = 2.11$$

$$= (0.928)(0.0874)(2.11 + 0.9) + 0.606$$

$$= 0.850$$

$$(\theta_s/\theta_o)^{\frac{1}{2}} = 3.21$$

$$N_s = 0.236$$

$$G_s = 1.043$$

$$P_{T3}/P_1 = 0.815$$

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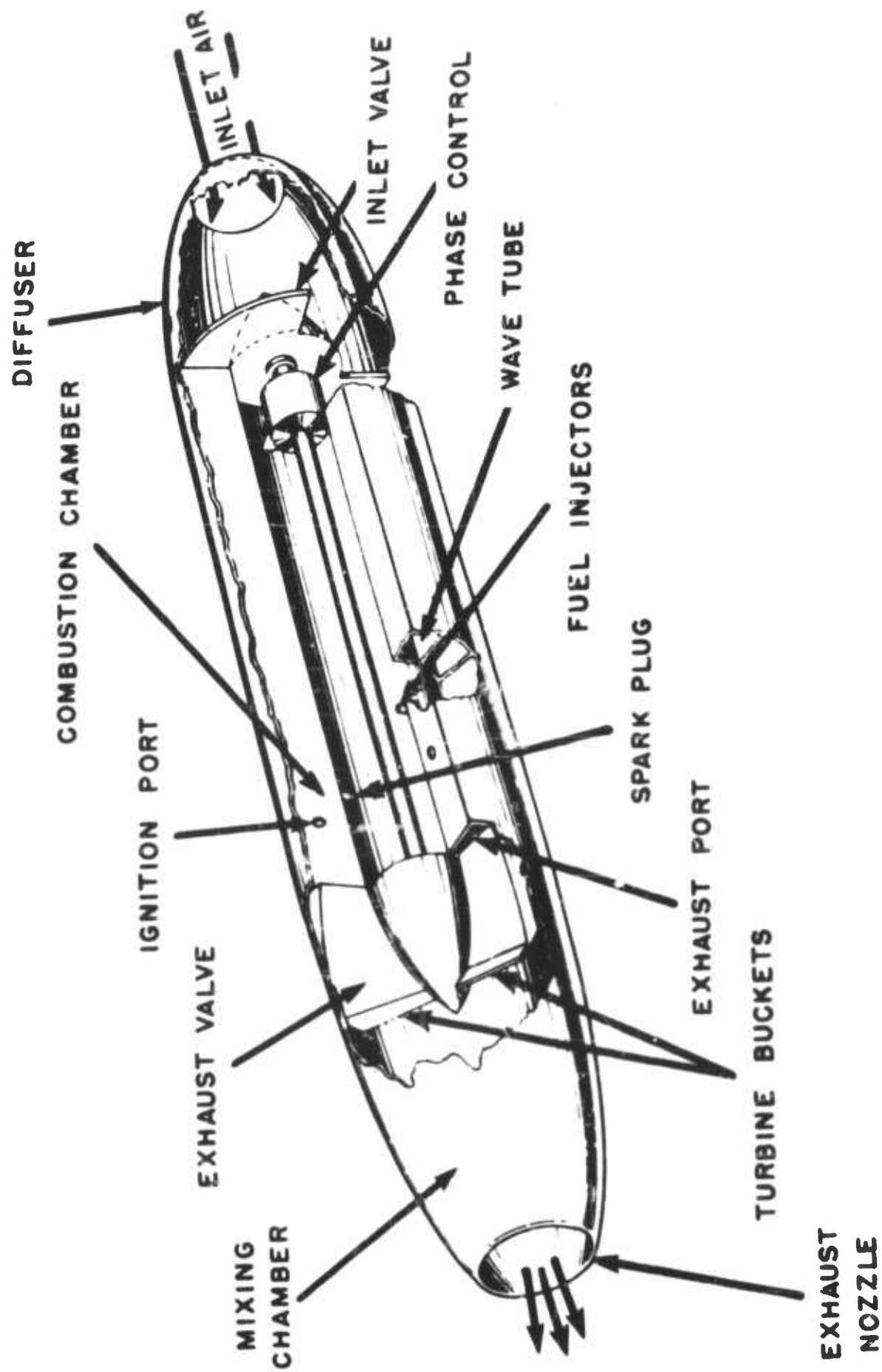


Fig. 1 WAVE ENGINE PROPULSION UNIT

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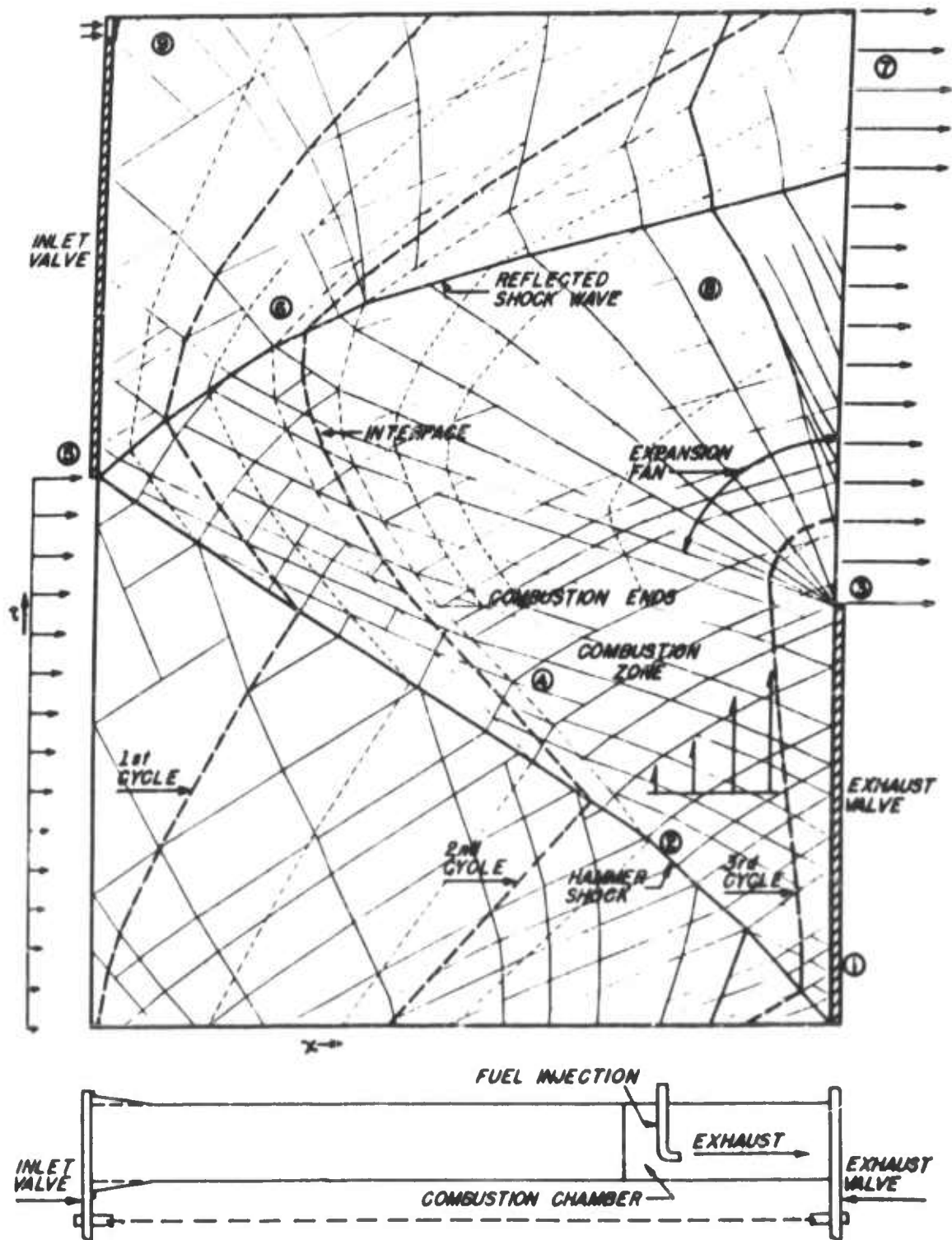


Fig. 2 WAVE DIAGRAM OF ONE ENGINE CYCLE
CALCULATED BY THE METHOD OF CHARACTERISTICS
MACH NO. = 0.66 AIR FUEL RATIO = 33

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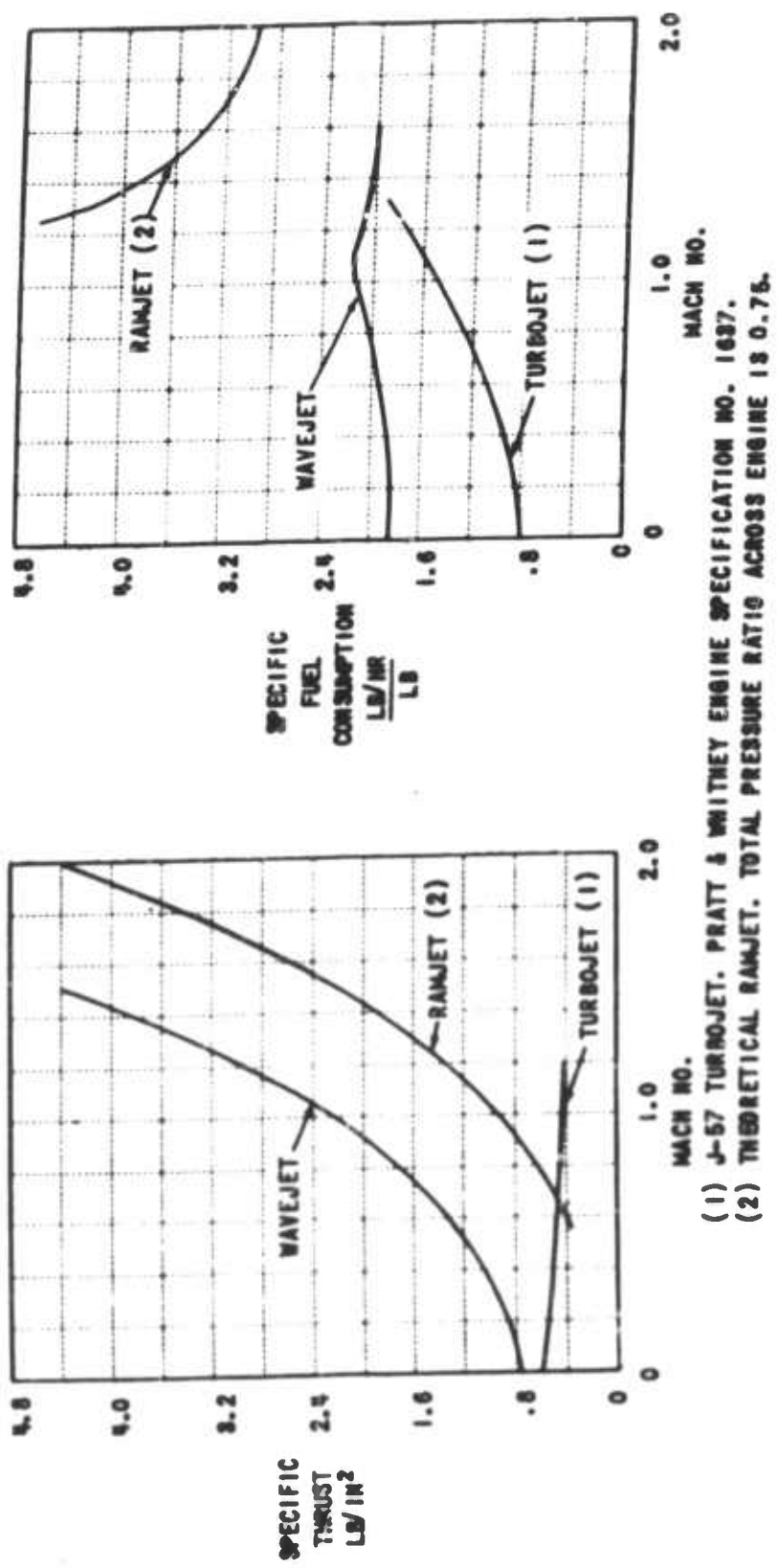


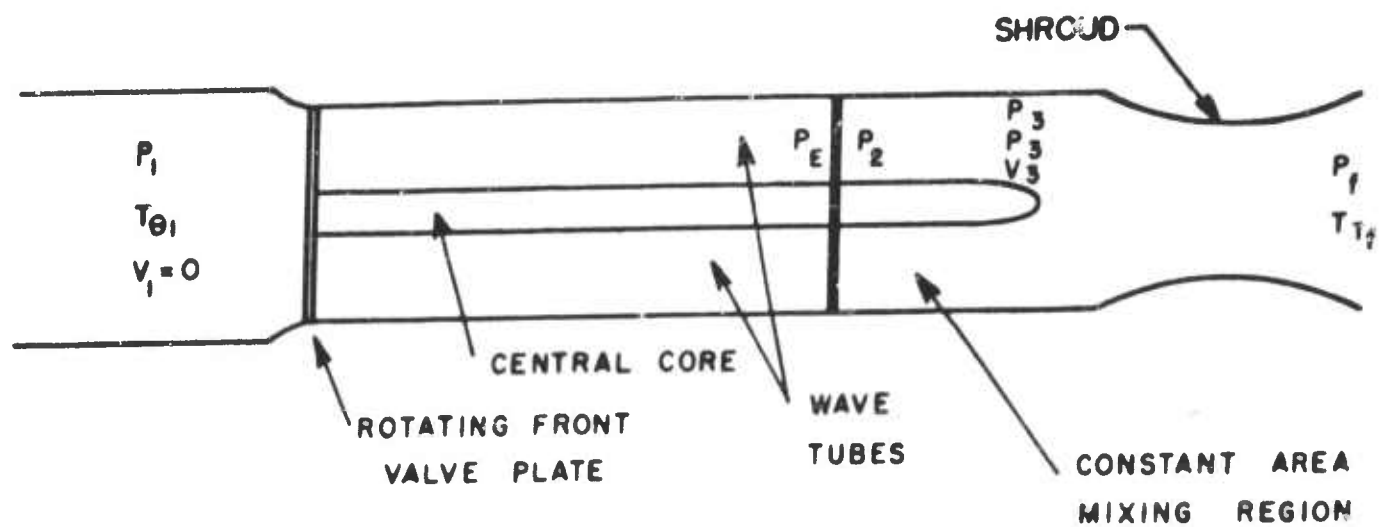
Fig. 3

PERFORMANCE COMPARISONS OF THEORETICAL SHROUDED WAVEJET WITH TURBOJET AND RAMJET

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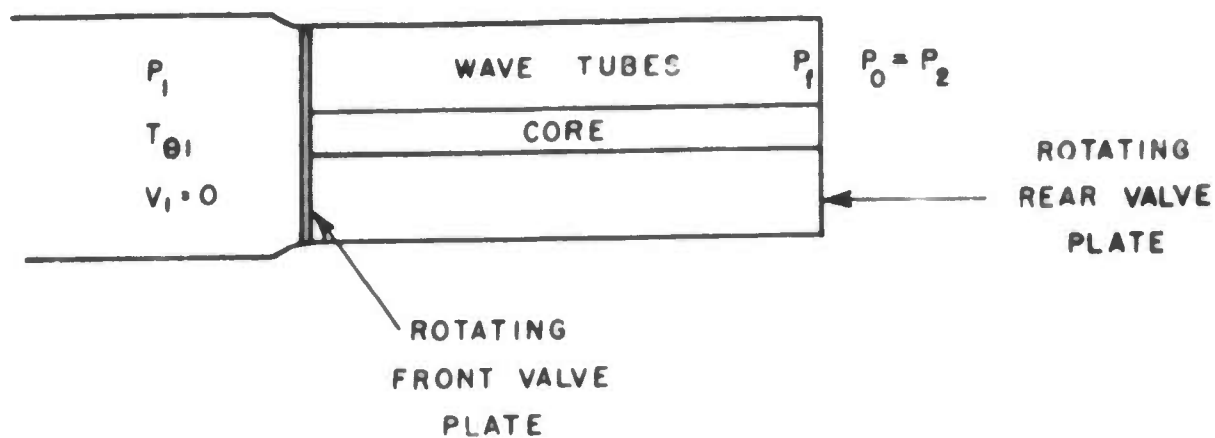
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MULTITUBE SHROUDED WAVEJET



CENTRAL CORE AREA = $1/3$ WAVE TUBE AREA

SHROUDED WAVEJET



CORE AREA = $1/3$ WAVE TUBE AREA

SIMPLE UNSHROUDED WAVEJET

Fig. 4 MULTITUBE WAVEJET CONFIGURATIONS

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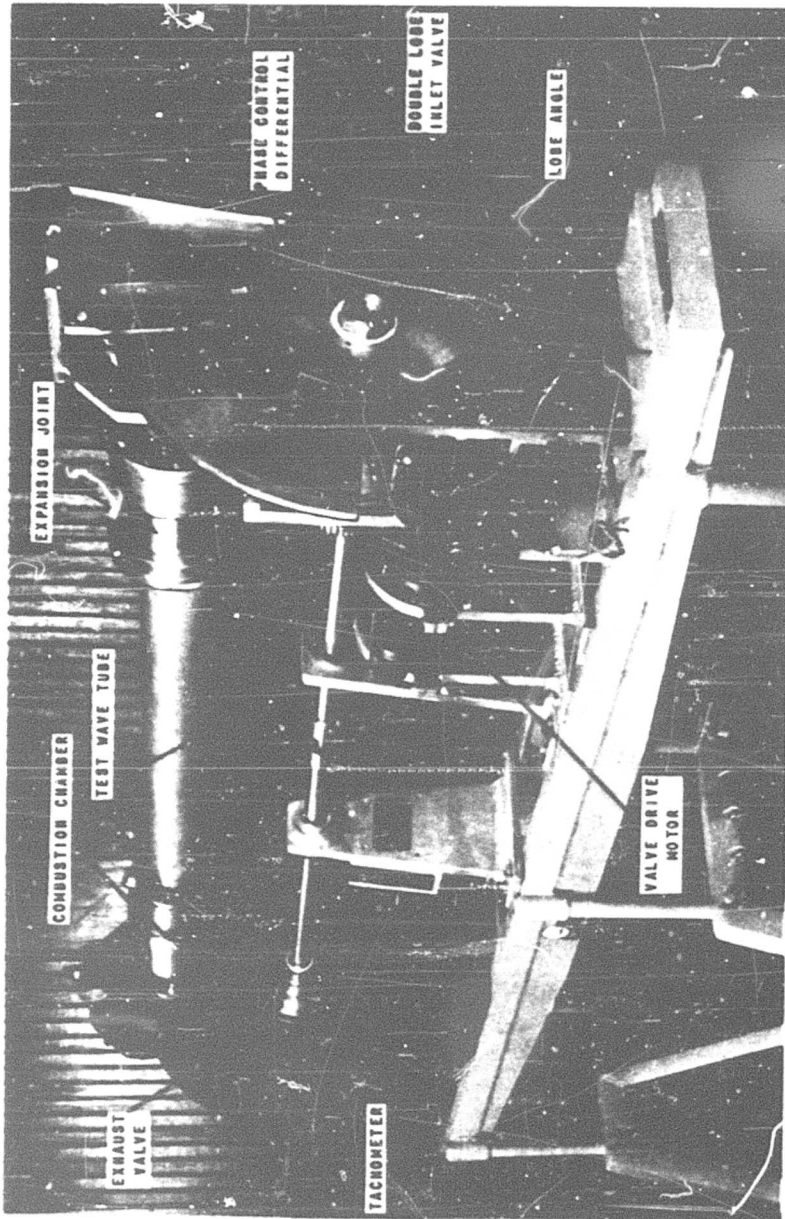
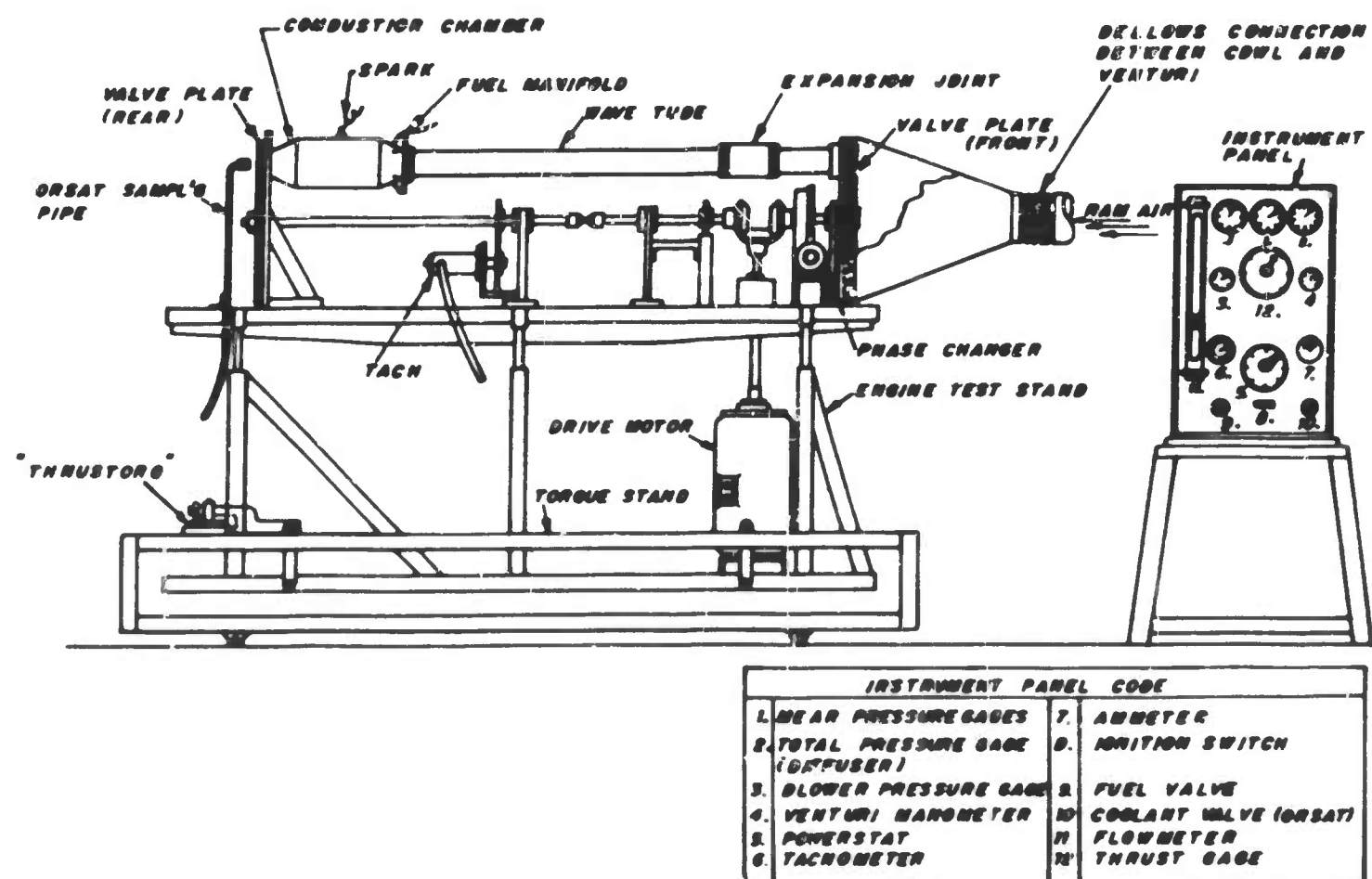


Fig. 5 SINGLE TUBE WAVEJET ENGINE AND TEST BED

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Fig. 6 SCHEMATIC DIAGRAM OF THE SINGLE TUBE
WAVEJET ENGINE TEST MODEL MOUNTED IN TEST BED

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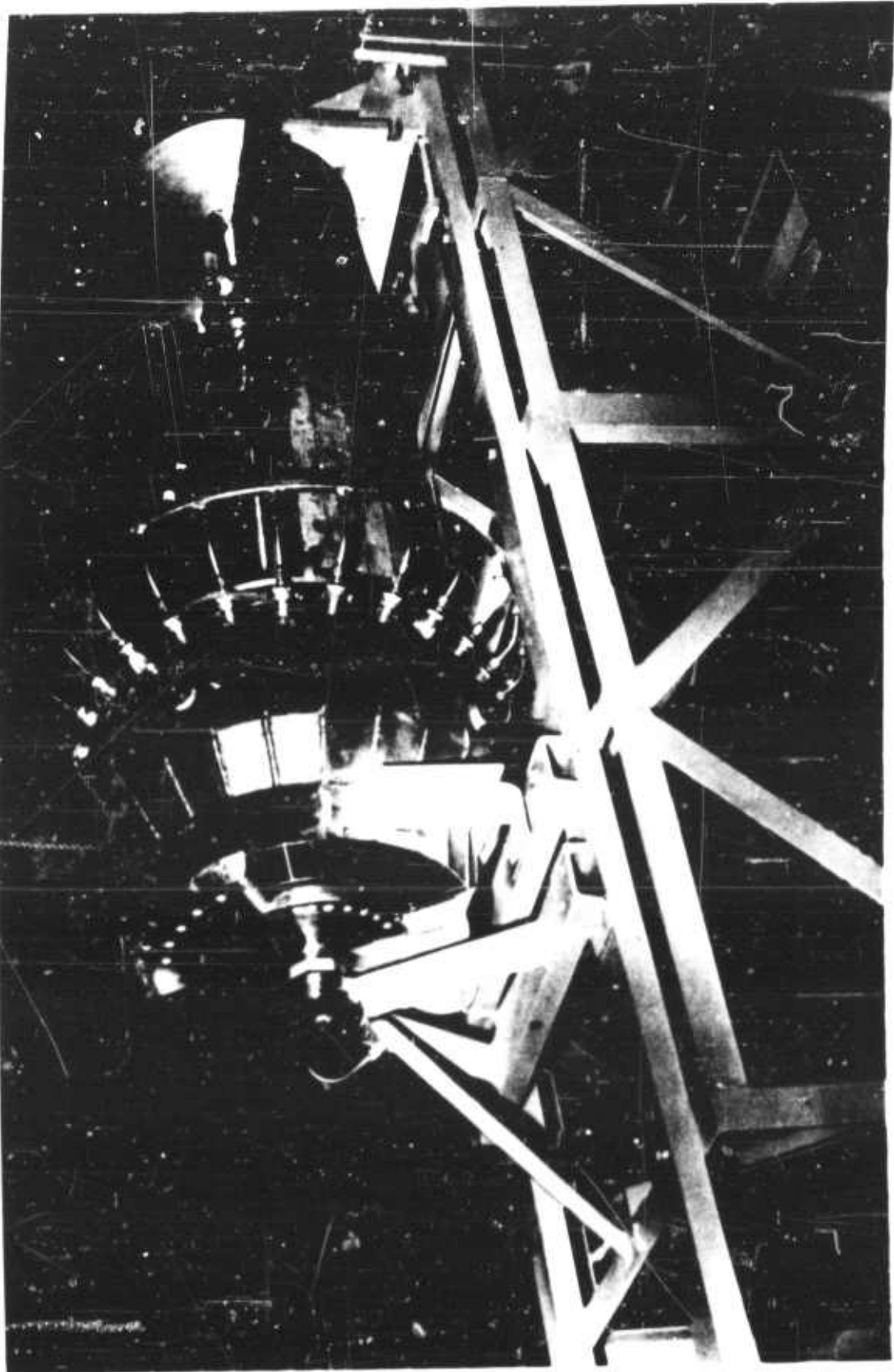


Fig. 7 MULTITUBE WAVEJET WITH TOP WAVE GUIDES REMOVED

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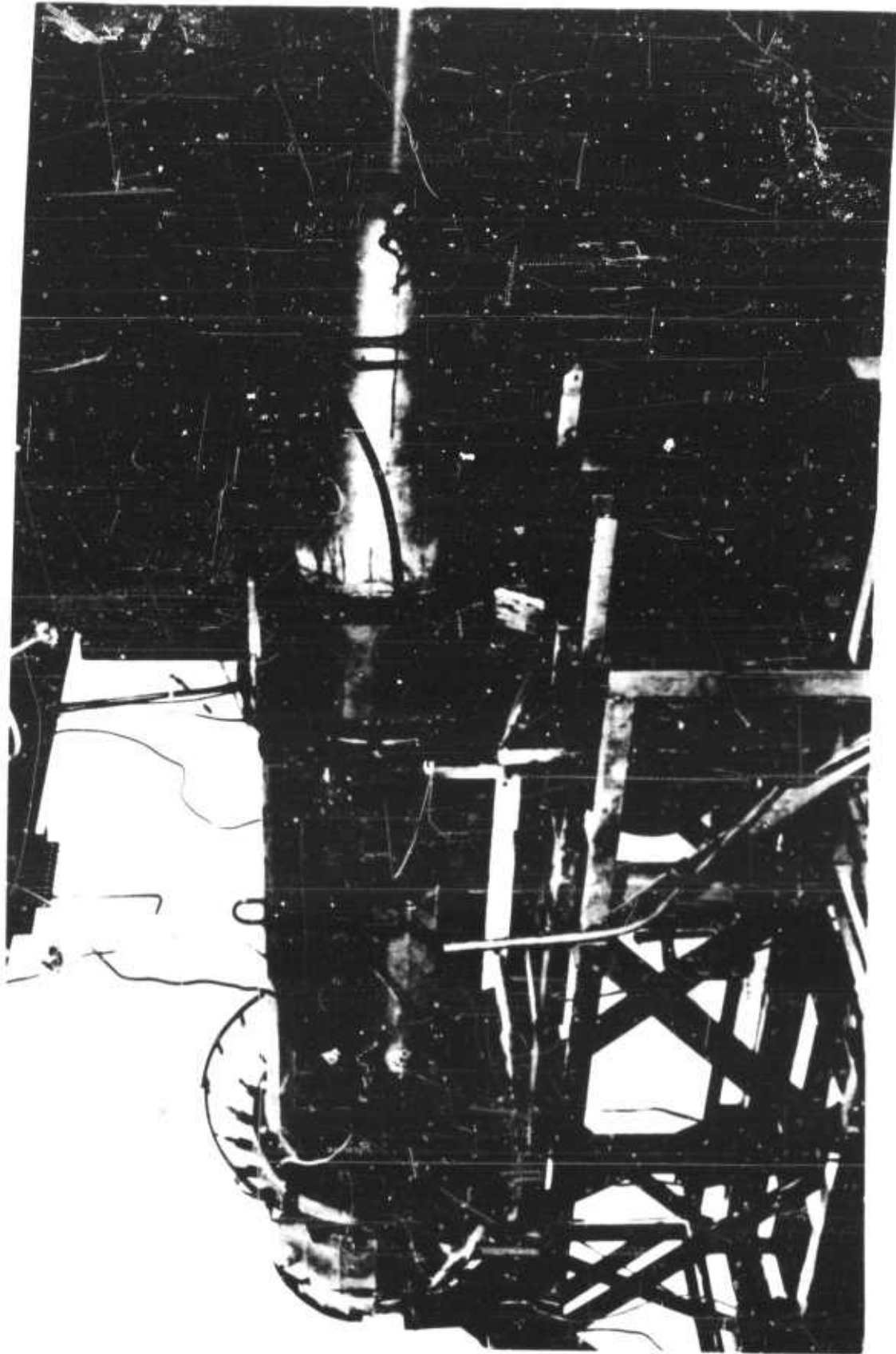


Fig. 8 MULTITUBE WAVEJET TEST MODEL WITH INLET RAM AIR COWLING

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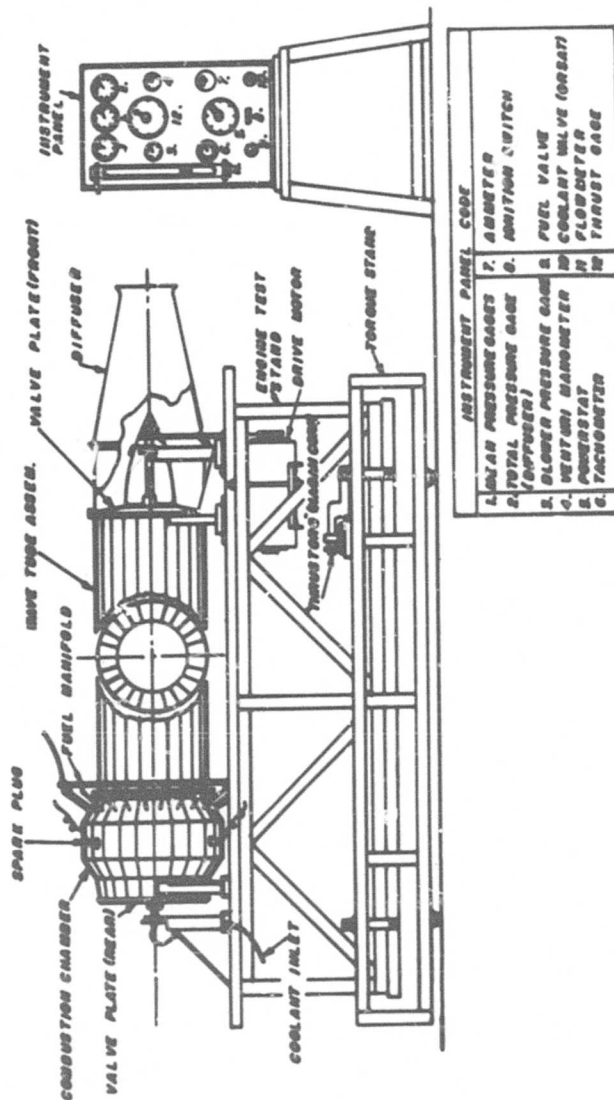


Fig. 9 SCHEMATIC DIAGRAM OF THE MULTITUBE WAVEJET ENGINE TEST MODEL

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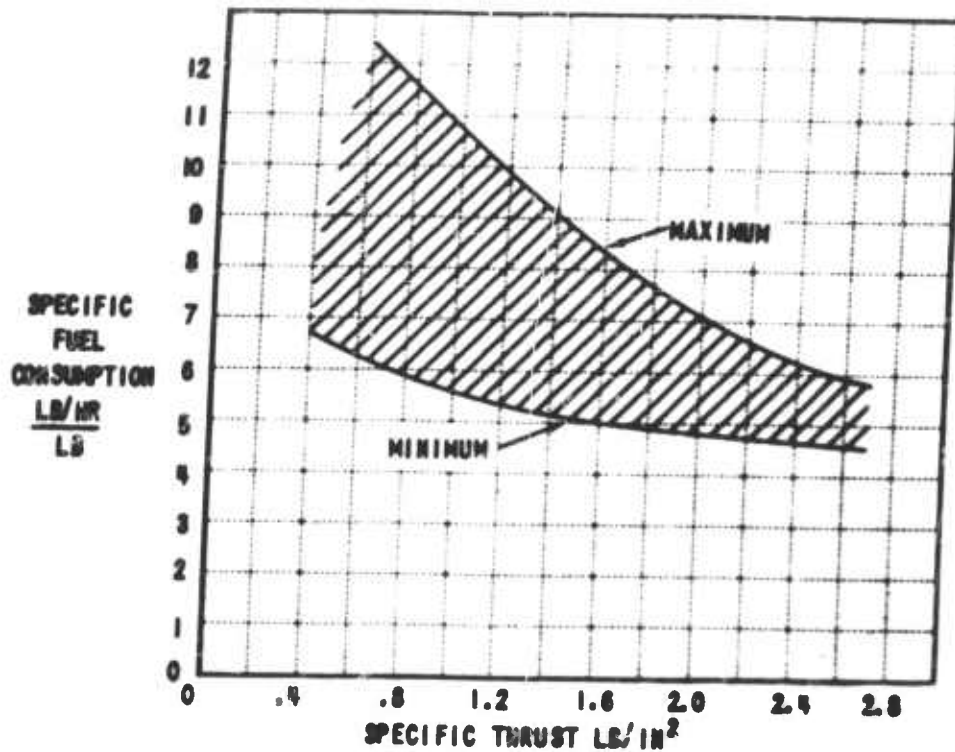


Fig. 10

EXPERIMENTAL VARIATION OF AVERAGE MAXIMUM AND MINIMUM SPECIFIC FUEL CONSUMPTION WITH SPECIFIC THRUST FOR CONSTANT AREA WAVEJET

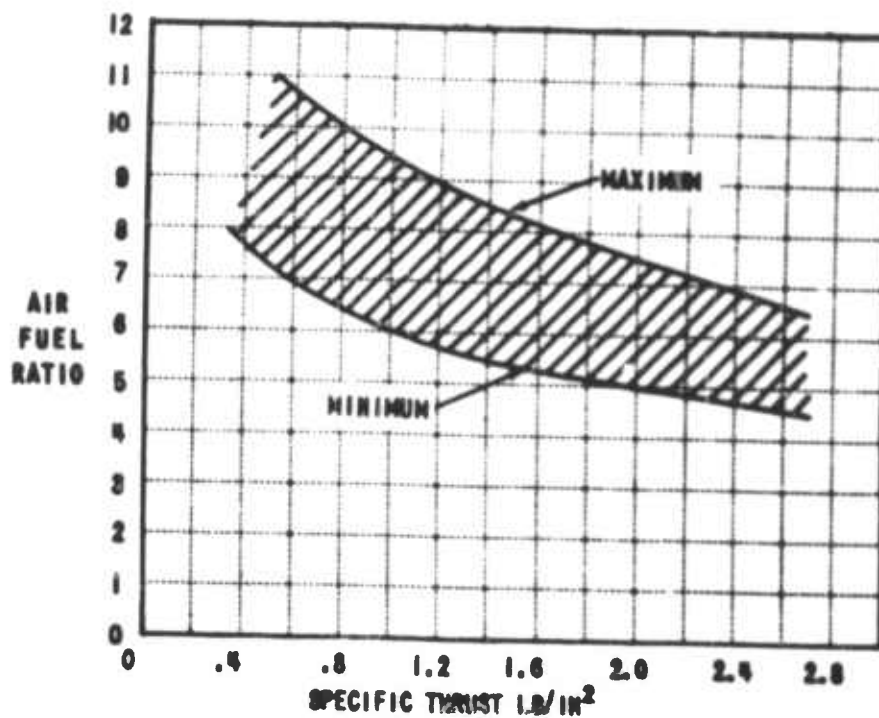


Fig. 11

AVERAGE MAXIMUM AND MINIMUM AIR FUEL RATIO VS. SPECIFIC THRUST FOR SINGLE TUBE CONSTANT AREA WAVEJET

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Fig. 12 SINGLE TUBE WAVEJET CHOKED EXHAUST

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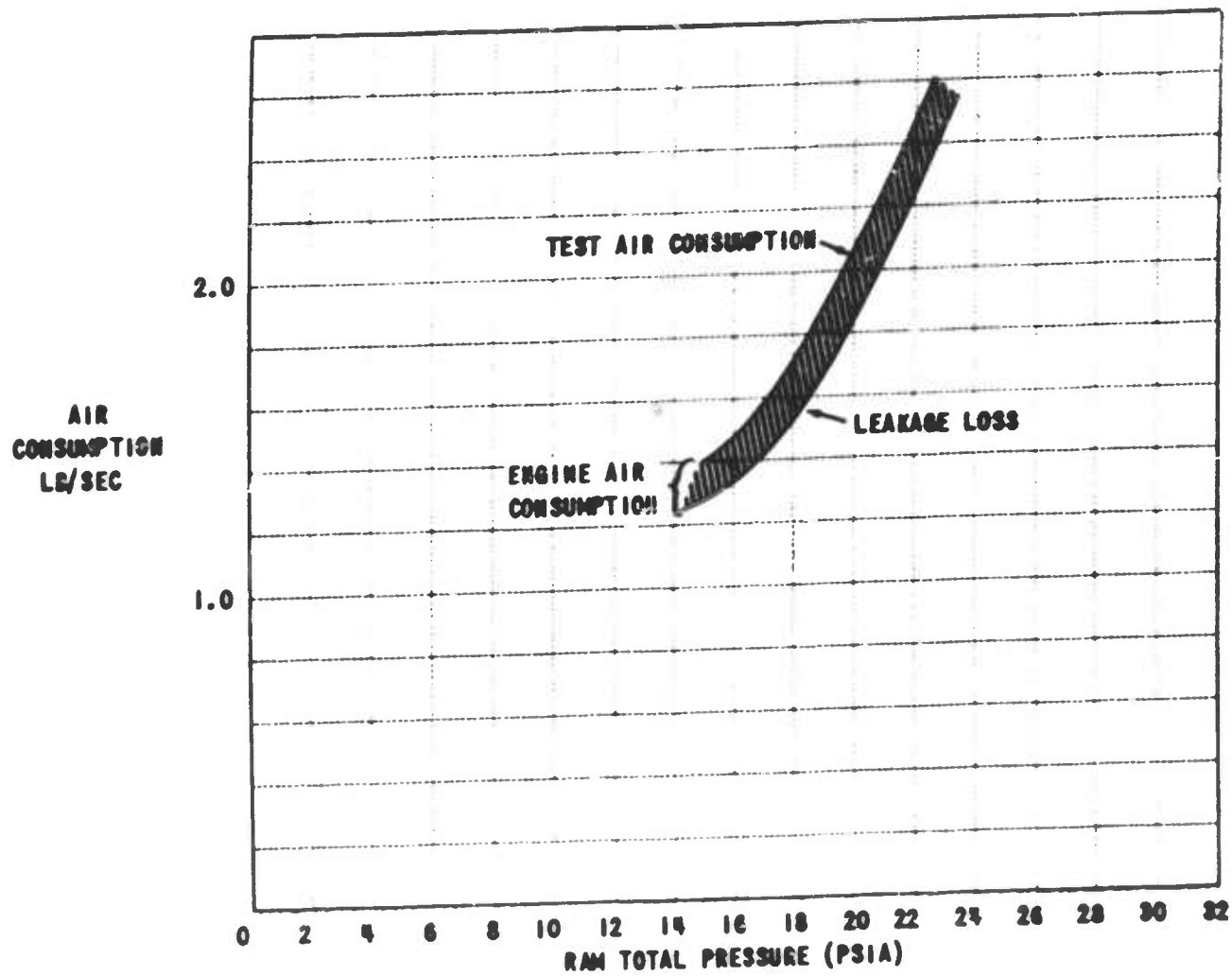


Fig. 13
SINGLE TUBE WAVEJET ENGINE AIR CONSUMPTION
BASED ON PRESSURE SURVEY RAKE

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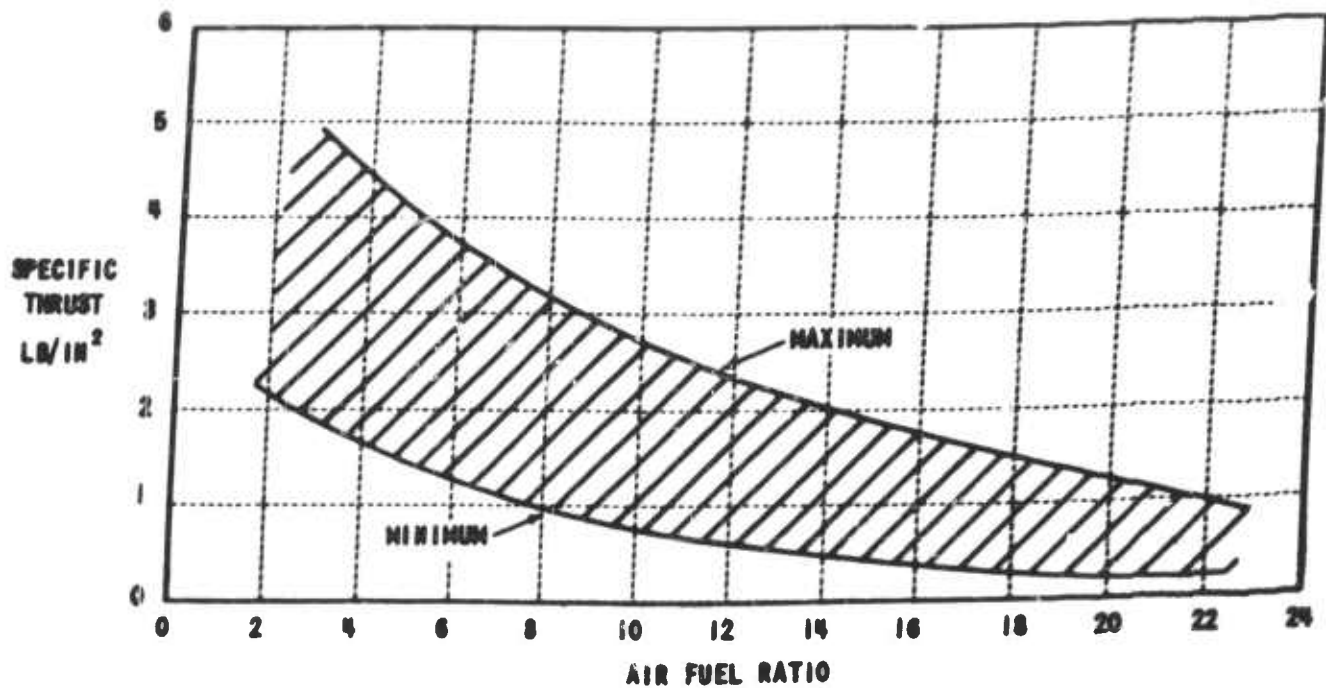


Fig. 14
AVERAGE MAXIMUM AND MINIMUM SPECIFIC THRUST OF
SINGLE TUBE CONSTANT AREA WAVEJET VS. AIR FUEL RATIO

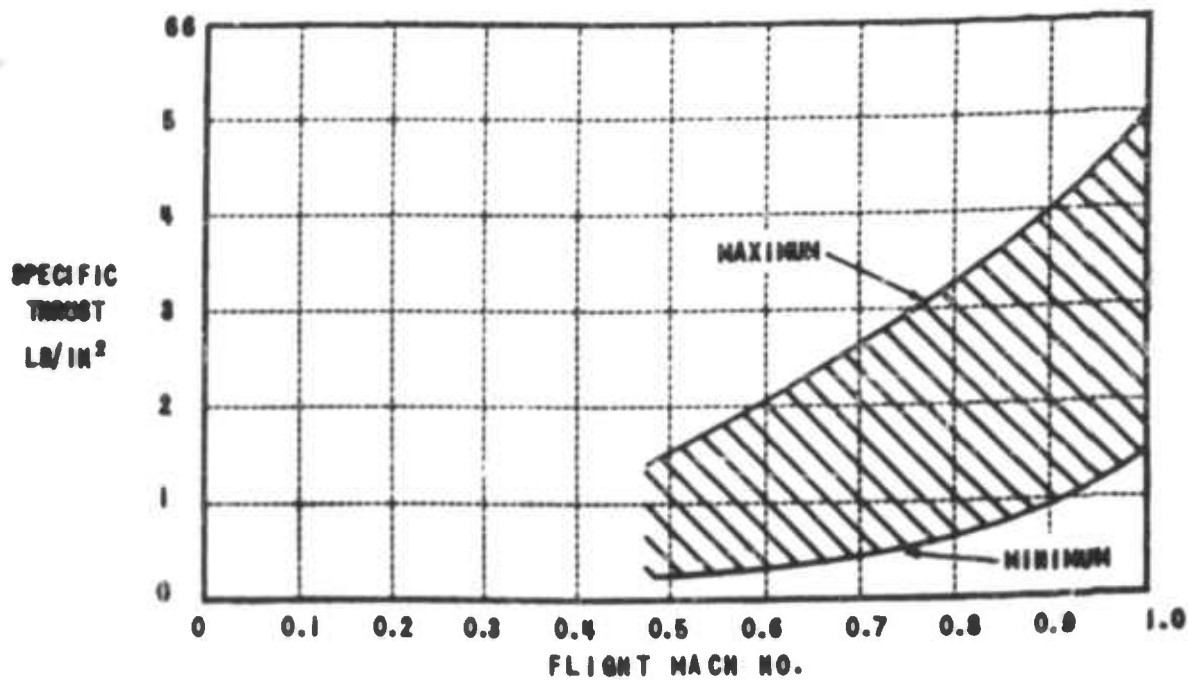


Fig. 15
AVERAGE MAXIMUM AND MINIMUM SPECIFIC THRUST VS.
FLIGHT MACH NUMBER FOR SINGLE TUBE CONSTANT AREA WAVEJET

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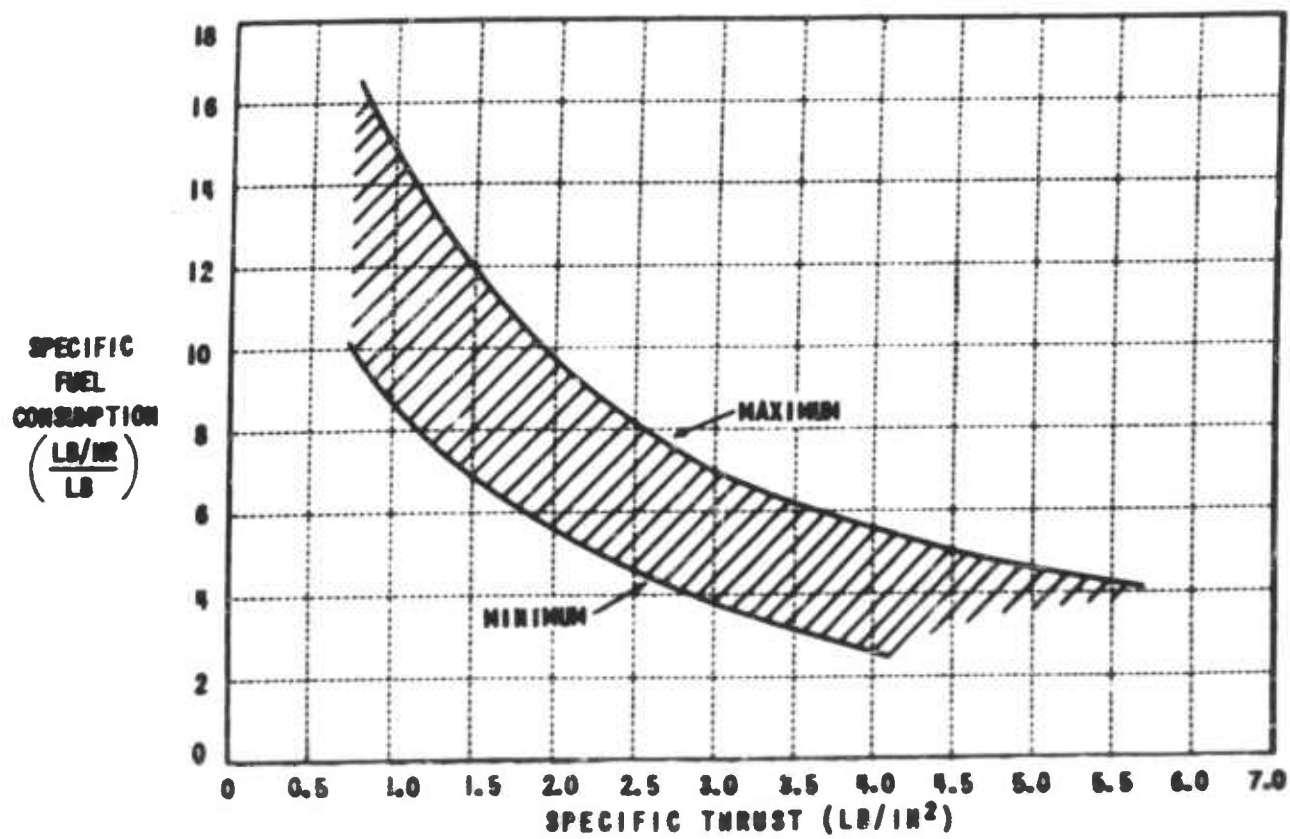


Fig. 16
AVERAGE MAXIMUM AND MINIMUM SPECIFIC FUEL CONSUMPTION VS.
SPECIFIC THRUST FOR SINGLE TUBE CONSTANT AREA WAVEJET

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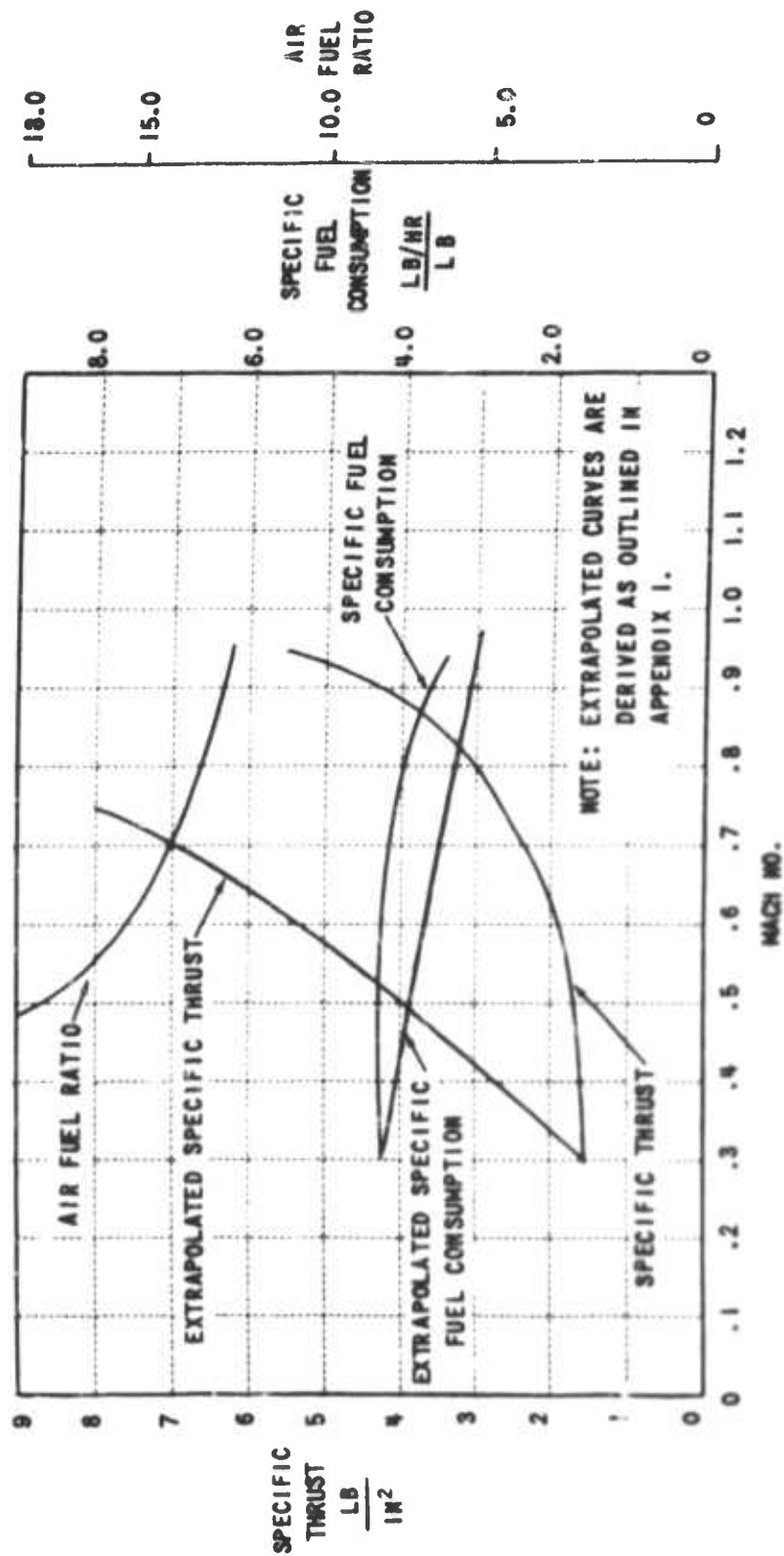


Fig. 17

BEST EXPERIMENTAL SINGLE TUBE CONSTANT AREA WAVEJET TEST RESULTS

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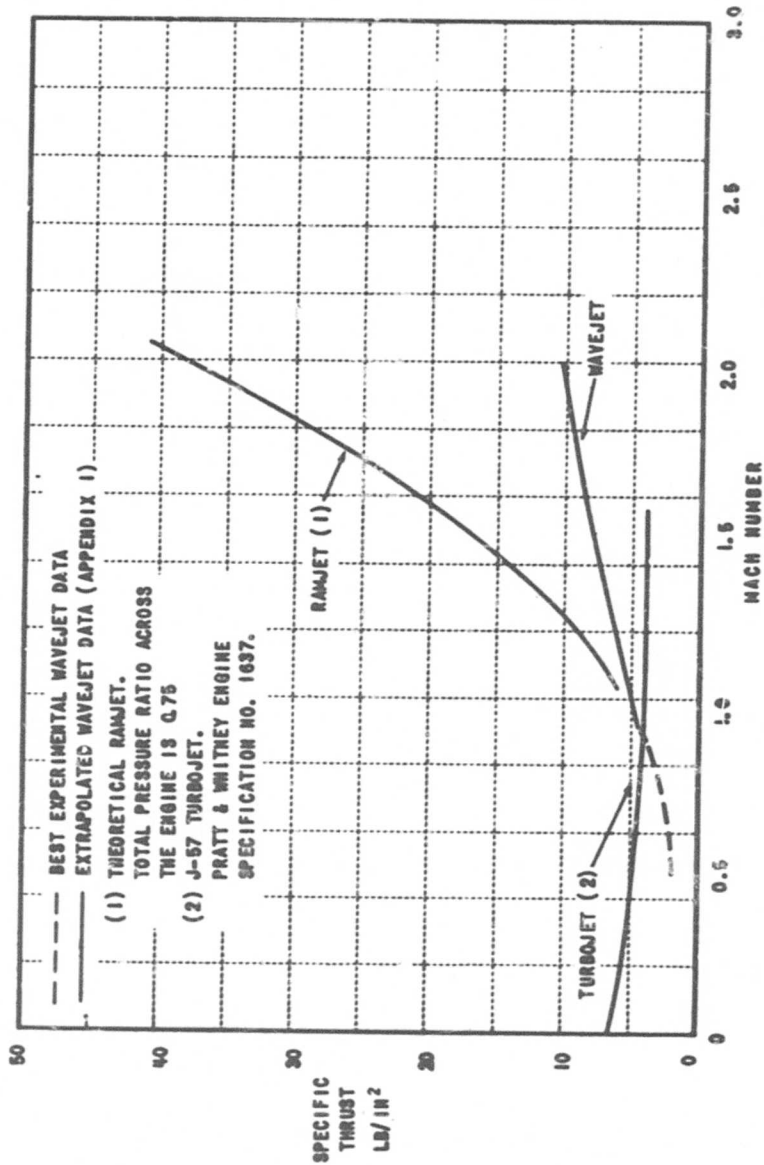


Fig. 18

SPECIFIC THRUST VS. MACH NUMBER COMPARISONS OF BEST EXPERIMENTAL AND
EXTRAPOLATED EXPERIMENTAL CONSTANT AREA WAVEJET AND RAMJET AND TURBOJET AT SEA LEVEL

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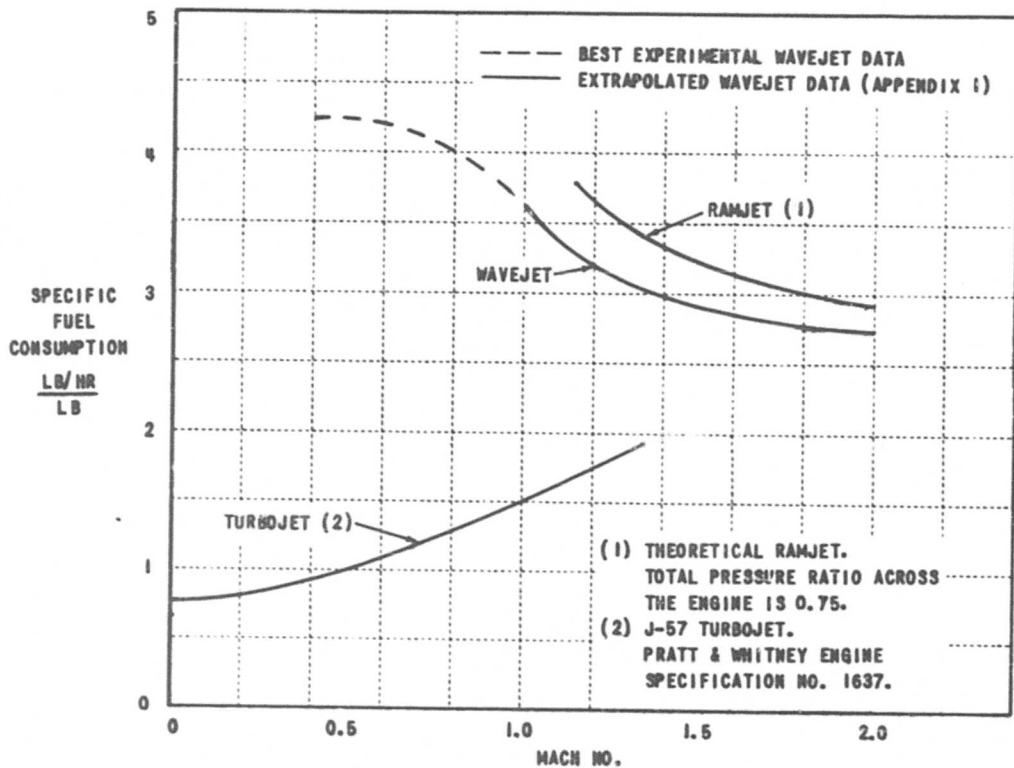


Fig. 19
SPECIFIC FUEL CONSUMPTION VS. MACH NUMBER COMPARISONS OF
BEST EXPERIMENTAL AND EXTRAPOLATED EXPERIMENTAL CONSTANT AREA
WAVEJET AND RAMJET AND TURBOJET AT SEA LEVEL

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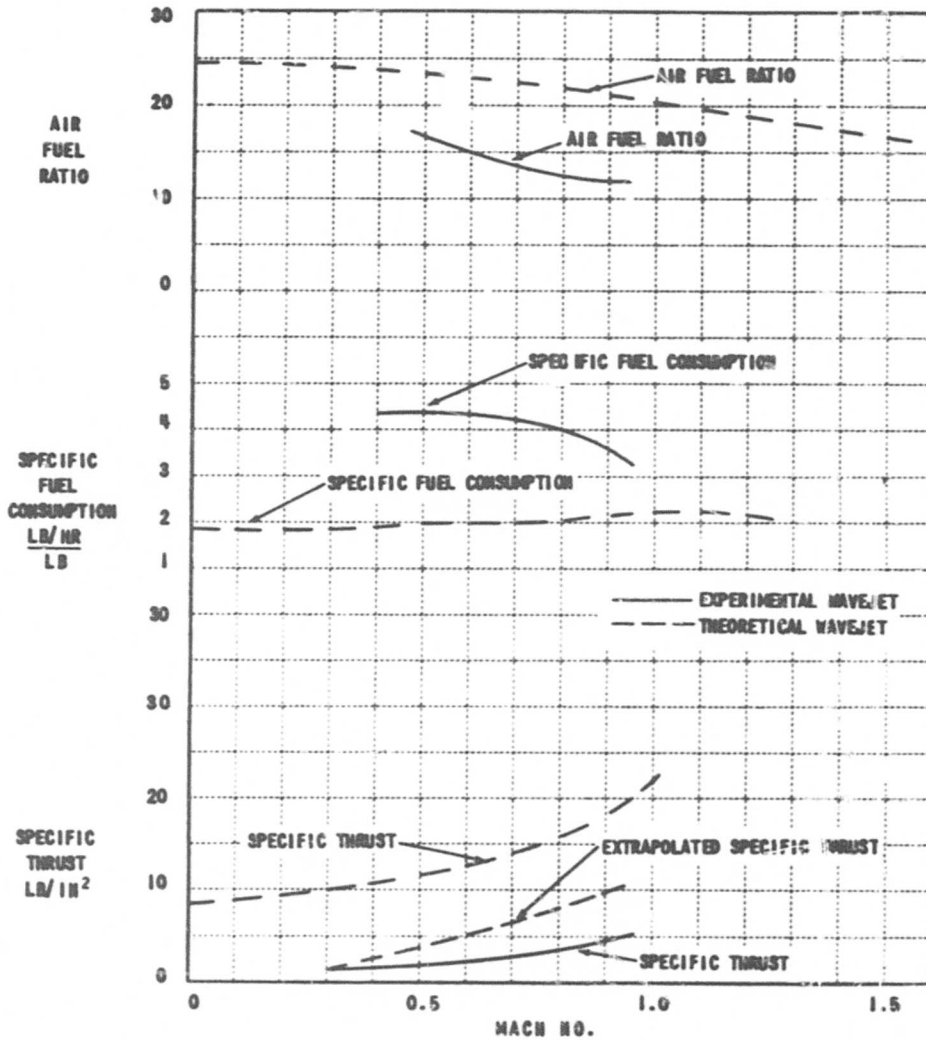


Fig. 20
PERFORMANCE COMPARISONS OF
BEST EXPERIMENTAL CONSTANT AREA WAVEJET
AND THEORETICAL CONSTANT AREA WAVEJET

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